08/14/2019
SFF 2019
1045 Hrs.
Room 416 AB

Process-structure-property Relationships in the Coating of Stellite on Inconel 718 by Directed Energy Deposition Process

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MECH 498/898 Additive Manufacturing Project Team

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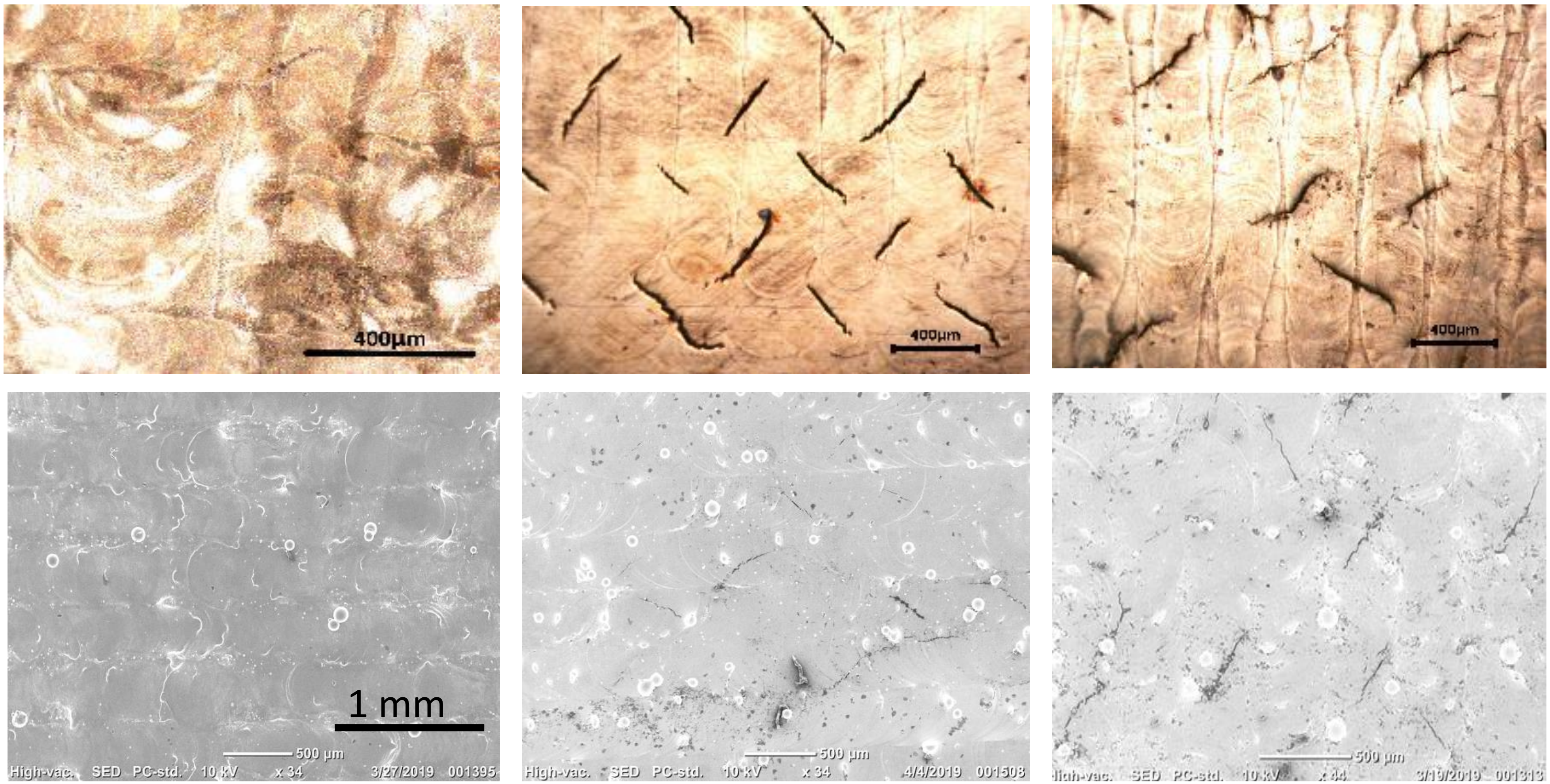
CMMI 1752069 (CAREER, Smart Additive Manufacturing)

Goal

Flaw-free deposition of Stellite 21 wear coating on Inconel 718



Low Preheat and Low Power | No Preheat and High Power | High Preheat and High Power

Objectives

Flaw-free deposition of Stellite 21 wear coating on Inconel 718

1) Understand and explain the metallurgy and processing science of flaw formation.

2) In-process detection and prevention of flaw formation

Outline

- Background and Prior Work
- Methods
  - Experimental Plan & Setup
  - Instrumentation of Sensor Array
- Results
  - Microstructure characterization (Optical, XCT, SEM)
  - Hardness testing
- Summary & Future Work

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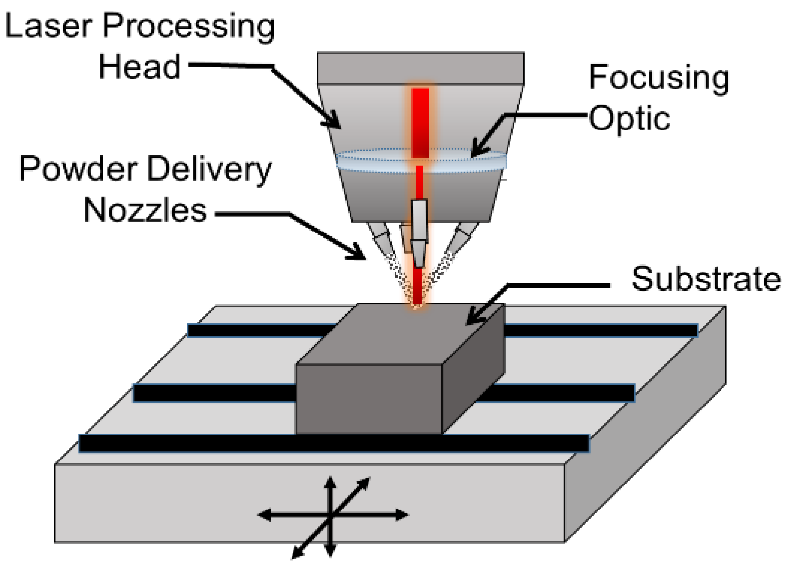
Directed Energy Deposition of Stellite 21



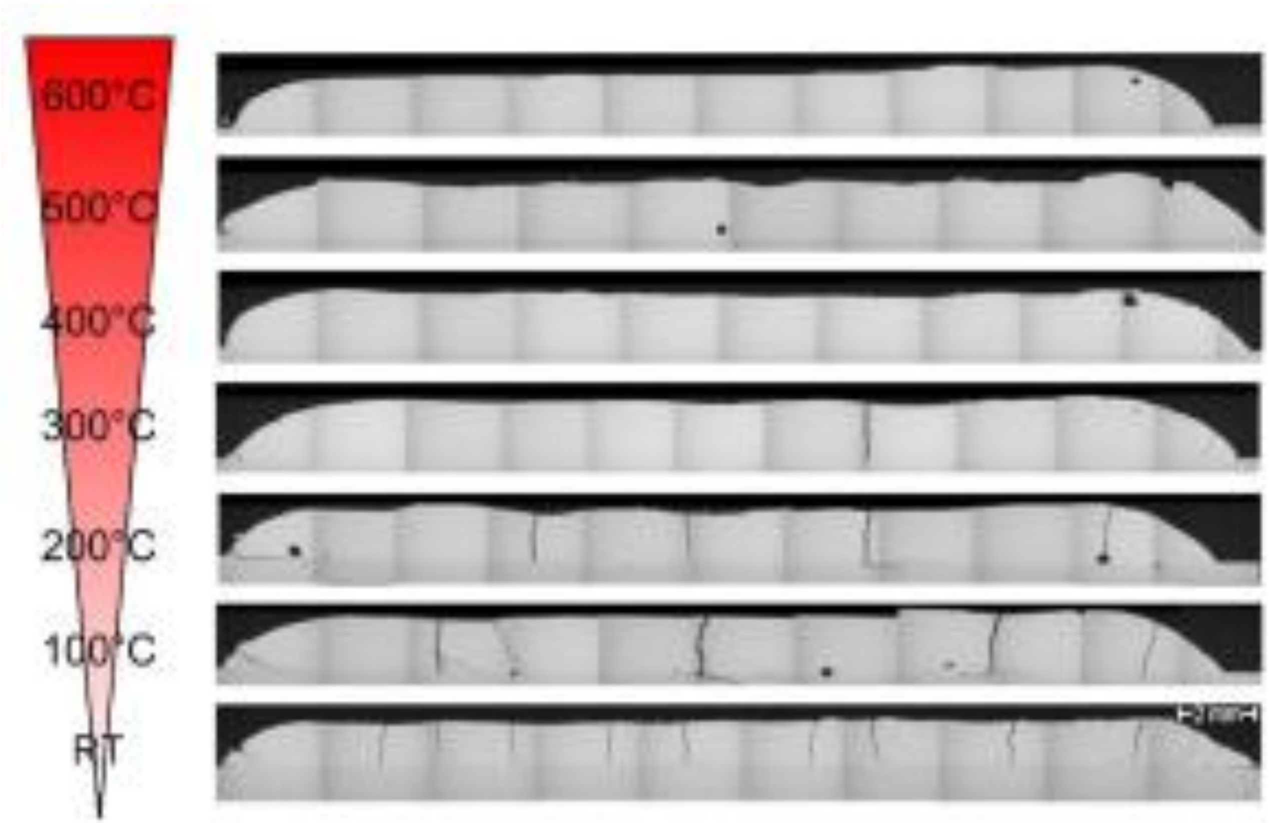
- Stellite is a cobalt-based ceramic material. Trademark of Kennametal.
- Application: Wear-resistant coating for parts operating in high-temperature conditions. E.g., automotive valves, machine gun barrels, and cutting tools.
- Directed Energy Deposition (DED), allows cladding Stellite onto free-form surfaces, and apply a graded coating.

Co	Cr	Mo	C	Ni	Others	Hardness**	Density	Melting Range
Base	26-29	4.5-6. 0	0.20-0.35	2.0-3. 0	Fe, Si, Mn	27-40 HRC** 290-430 HV**	8.33 g/cm^3 0.301 lb/in^3	2360-2615 °F 1295-1435 °C

Effects of Preheating

Preheating reduces crack formation.

Laser cladding of Stellite 20 on Ck45 (carbon steel)



Brueckner, F., Lepski, D., Nowotny, S., Leyens, C., and Beyer, E., 2012, "Calculating the stress of multi-track formations in induction-assisted laser cladding," International Congress on Applications of Lasers & Electro-Optics, pp. 176-182.

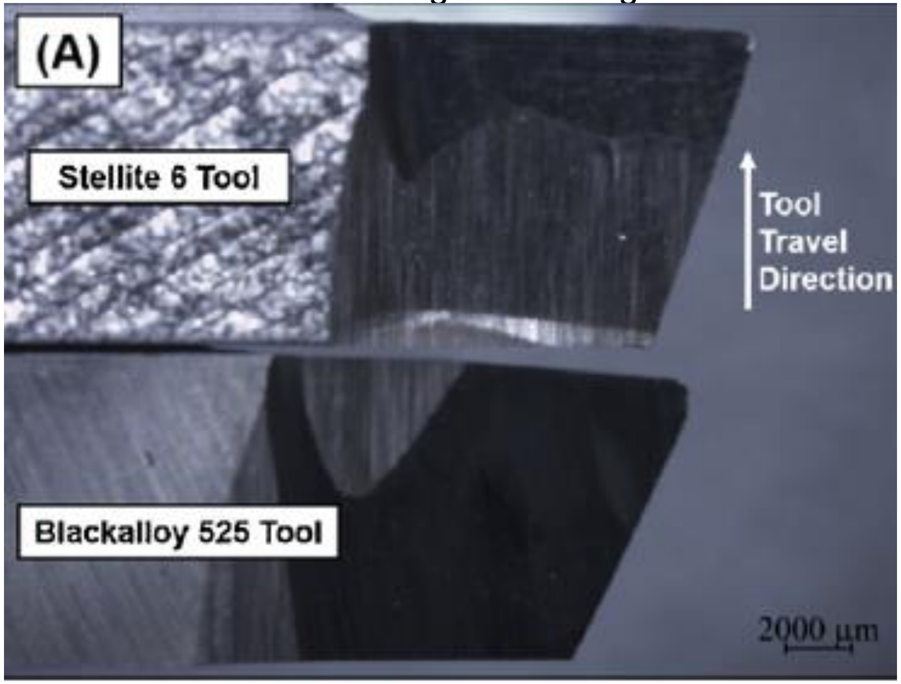
Energy density is a key determinant of coating wear resistant

DED-based Stellite coating for cutting tool applications.

$$E_V = \frac{P}{V \times T \times H} = 300\ \frac{J}{mm^3}$$

Laser Power (P): 410 W
Scan Speed (V): 5.5 mm/sec
Hatch Spacing (H): 0.5 mm
Layer thickness (T): 0.5 mm

Stellite 6 coatings on cutting tools.

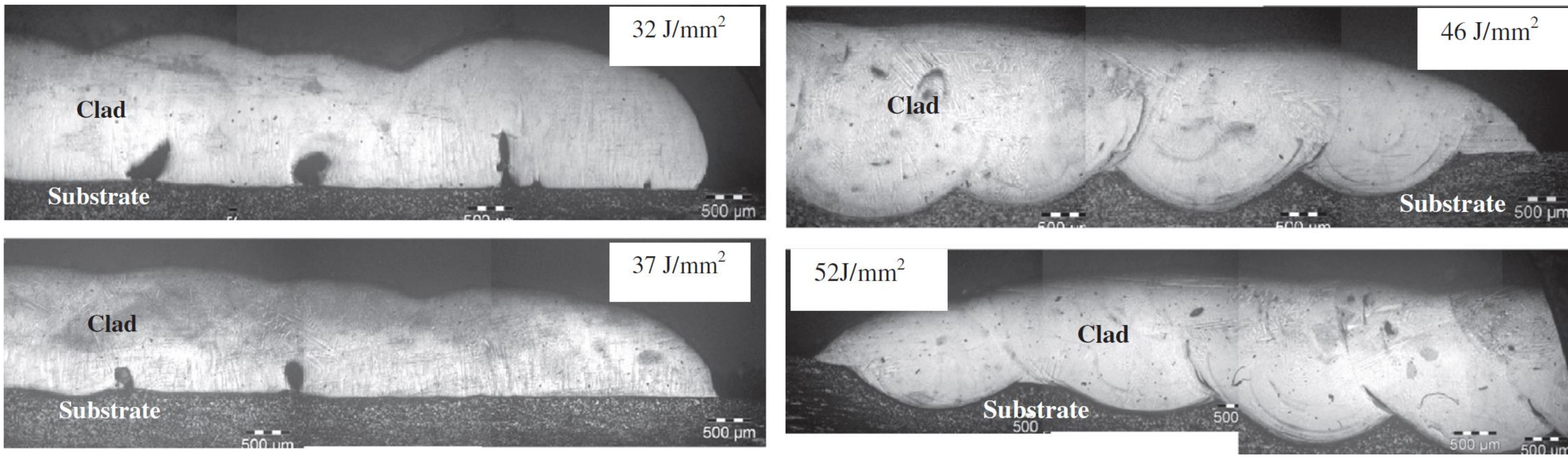


We used 225 and 280 $\frac{J}{mm^3}$ as starting points

Traxel, Kellen D., and Amit Bandyopadhyay. "First Demonstration of Additive Manufacturing of Cutting Tools Using Directed Energy Deposition System: Stellite™-Based Cutting Tools." *Additive Manufacturing*, vol. 25, 2019, pp. 460–468., doi:10.1016/j.addma.2018.11.019.

Energy density is related to hardness and flaw formation

Low energy density correlated to higher micro-hardness, reduced particle erosion, but increase in flaws.



$$E_A = \frac{P}{V \times D}\ \frac{J}{mm^2}$$

P = Laser Power [W]; V = Scan Rate [mm/s]; and D = Laser Spot Diameter [mm]

We used 30 and 40 $\frac{J}{mm^2}$ as starting points

Raghuvir Singh, Damodar Kumar, S.K. Mishra, S.K. Tiwari, Laser cladding of Stellite 6 on stainless steel to enhance solid particle erosion and cavitation resistance, Surface and Coatings Technology, Volume 251, 2014, Pages 87-97, ISSN 0257-8972, https://doi.org/10.1016/j.surfcoat.2014.04.008.

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Key Process Parameters

- Preheating
  - Use the laser (suitable for small parts)
  - Separate heating element (difficult to scale)
- Energy Density (Ev)
  - Laser Power and Velocity are machine constraints.
  - Ev is more transferable

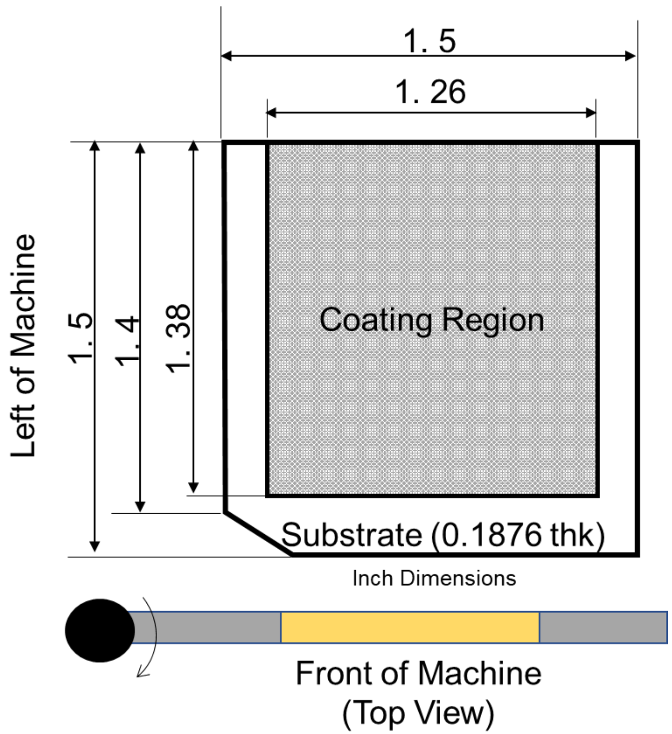
$$E_V = \frac{P}{V \times T \times H} \left[\frac{J}{mm^3} \right]$$

- Flow Rate
  - Material is ejected from the meltpool
  - Forced convection pushes material away
  - Powder bounces from the substrate

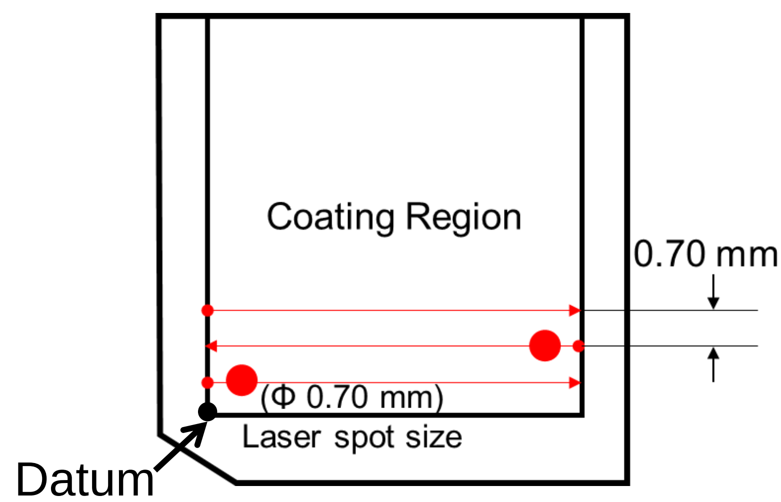
Experimental Plan

Inconel 718 coupon
(37.5 mm 37.5 mm × 4.76 mm)

Coating thickness 12 layers
(3 mm total coating, 0.250 mm layer height)

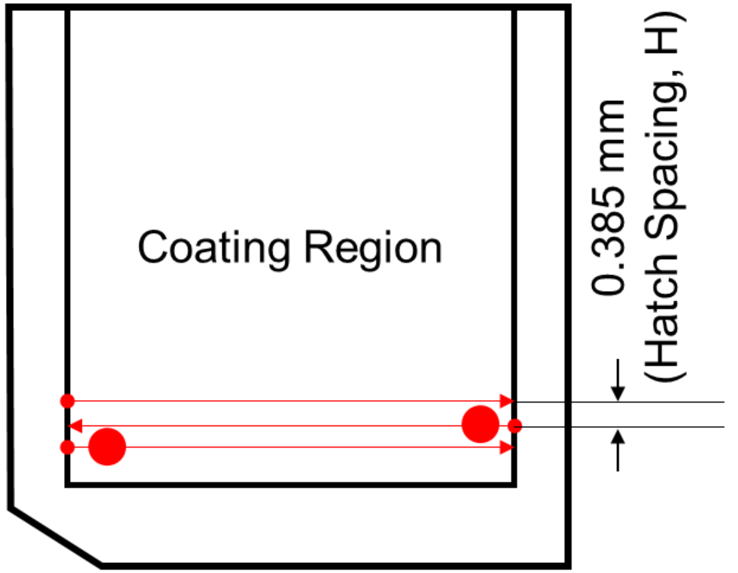


- Preheating begins with counterclockwise contour scan starting from the datum.
- Preheating (2 passes) is done with the laser
- Rectilinear scan path, no overlap.
- Start and end at the same point.
- Laser turns off at the end of the scan.

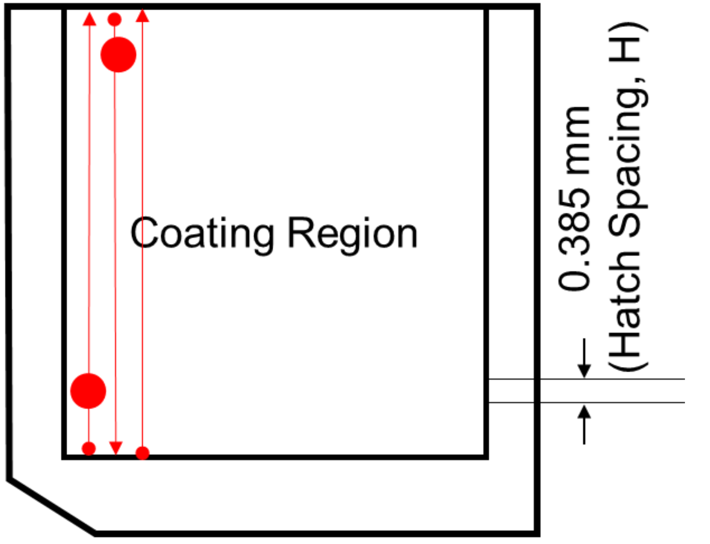


Experimental Plan

- Anti-clockwise contour between layers starting at the datum
- 12 deposition passes, rectilinear scan path, 95% overlap between hatches.
- Start and end at the same point.
- Laser turns off at the end of the scan



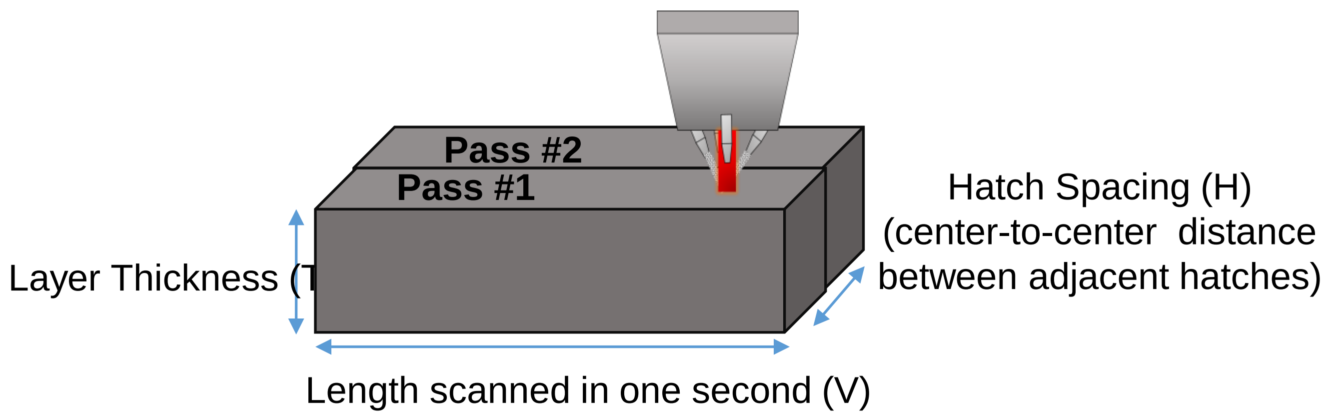
Odd Deposition Pass



Even Deposition Pass

Setting the Energy Density Parameters

Process Step	Laser Power P [W]	Scan Speed V [mm/s]	Hatch Spacing H [mm]	Layer Thickness T [mm]
Preheat (2 layers)	Varied (NP, 300, 350, 400)	12	0.7 (laser spot size)	N/A
Print (12 layers)	Varied (200, 225, 250, 275)	10.6 (recommended)	0.38 (1.5 × T)	0.25



$$E_V = \frac{P}{V \times T \times H} \ (J/mm^3)$$

E_V used in this experiment 200 $\frac{J}{mm^3}$ to 275 $\frac{J}{mm^3}$

Approximate printing time 60 minutes to 75 minutes

Setting Flow Rate

Minimum Flow Rate = Volume of Material Deposited in one minute × Density

$$= [V \times T \times H]\rho$$
$$= [10.6 \times 0.25 \times 0.38] \times 8.33 \times 10^{-3}$$
$$\approx 0.500\ [\mathrm{g \cdot s^{-1}}]$$

Minimum flow rate possible on the machine is 1.8 $g.s^{-1}$

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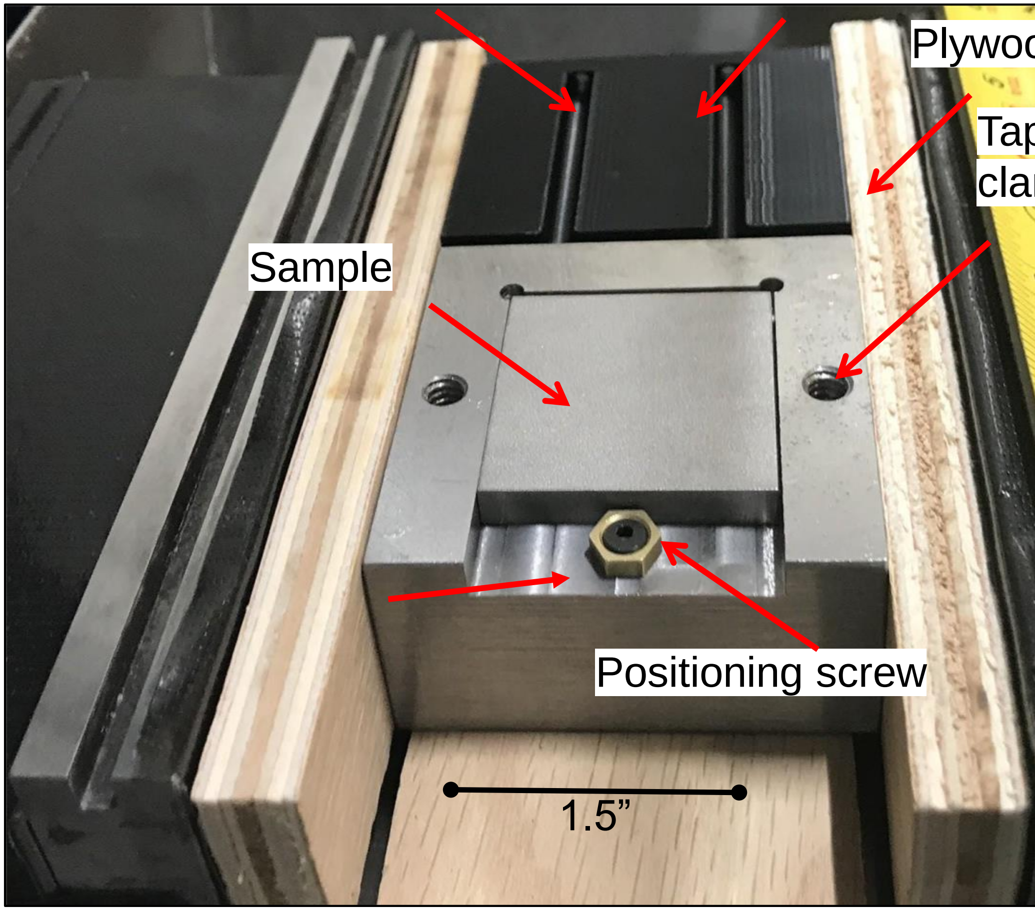
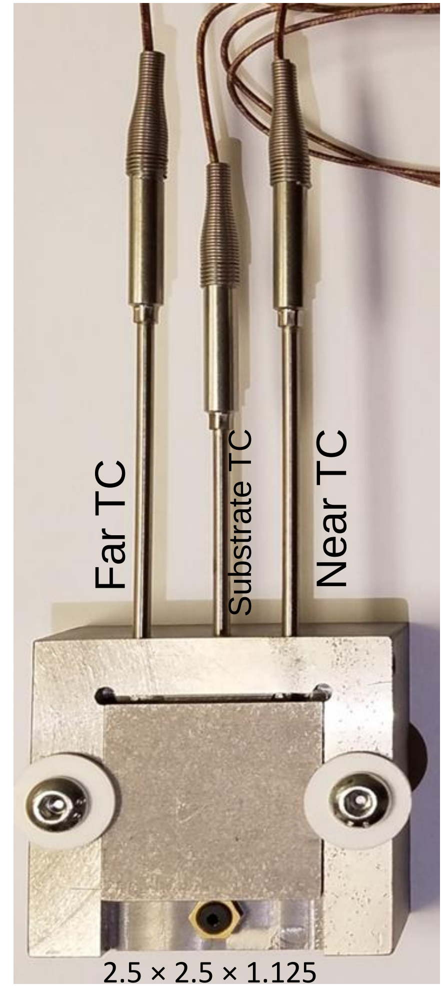
Fixture and Setup

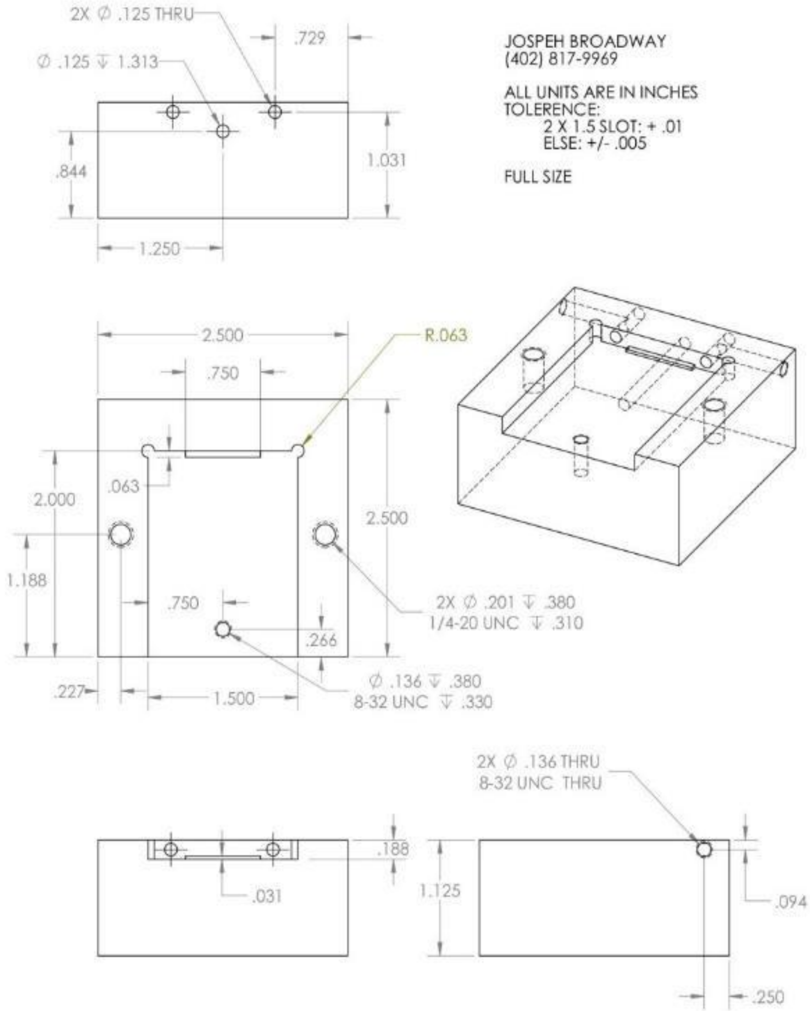


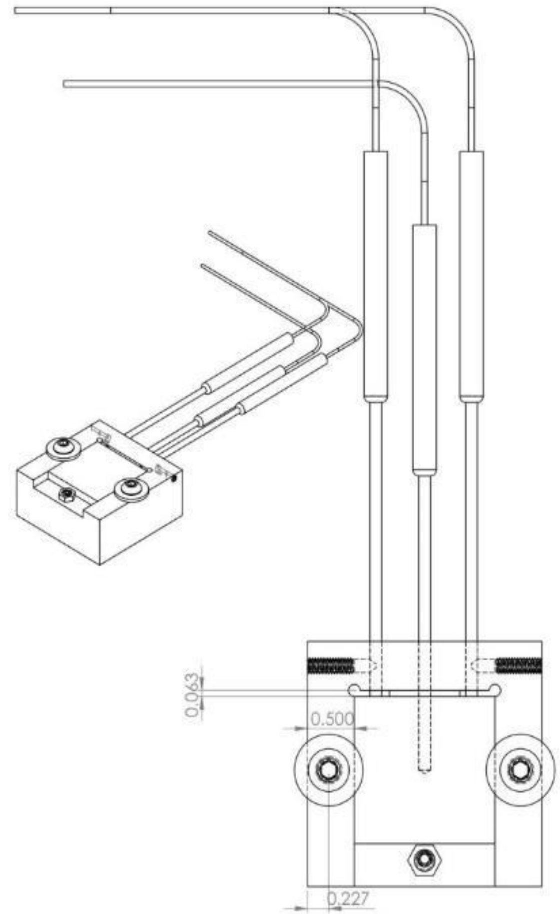
Build plate fixture inside the Optomec LENS machine



Inconel 718 clad K type Thermocouples (TC)

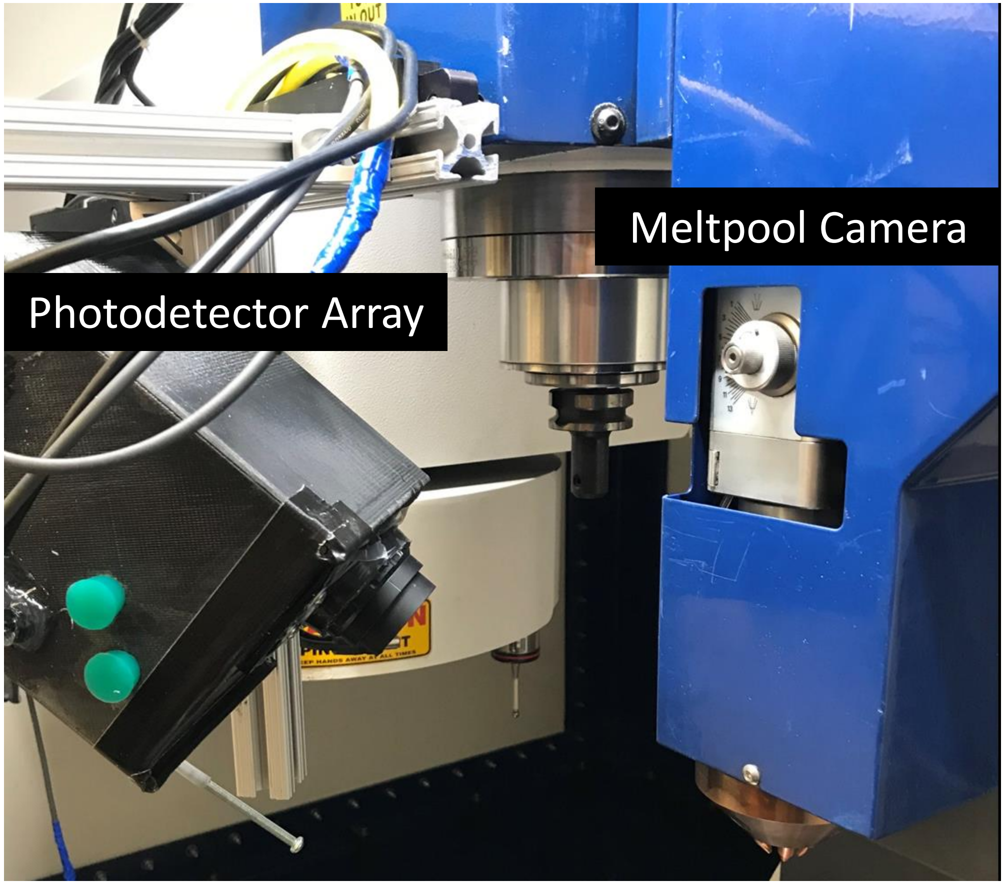
Fixture and Setup



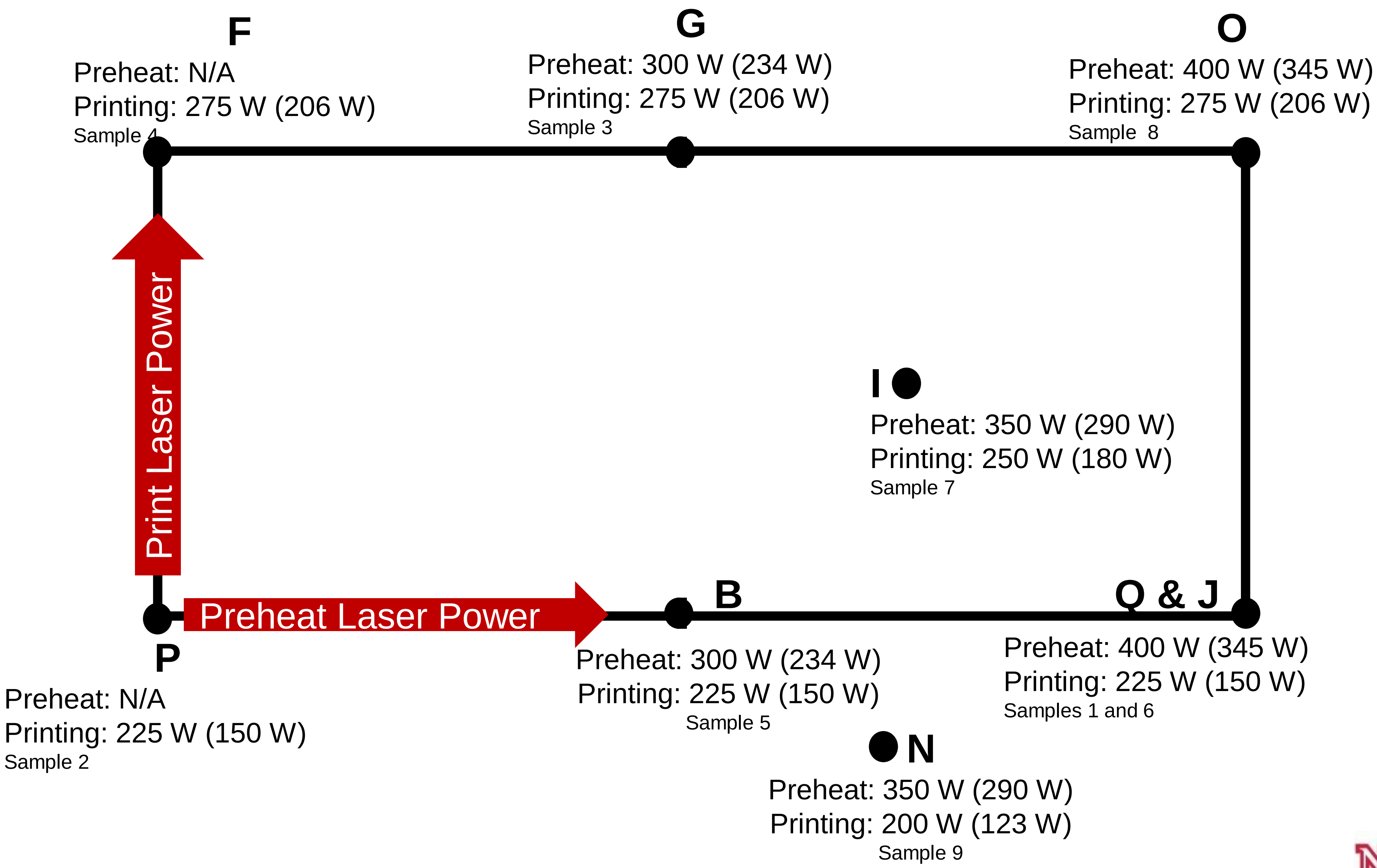


In-process Sensing Setup

Multiple sensors were instrumented on the machine, including a photodetector array, infrared thermal cameral, and a meltpool camera.



Evolutionary Optimization Experimental Plan



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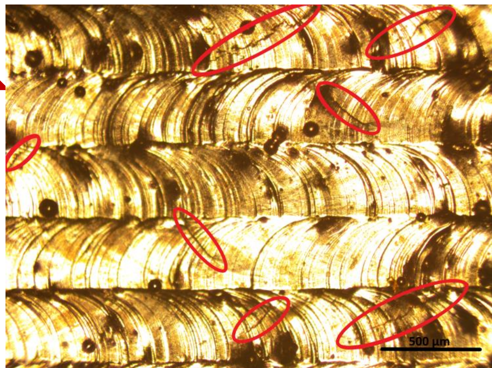
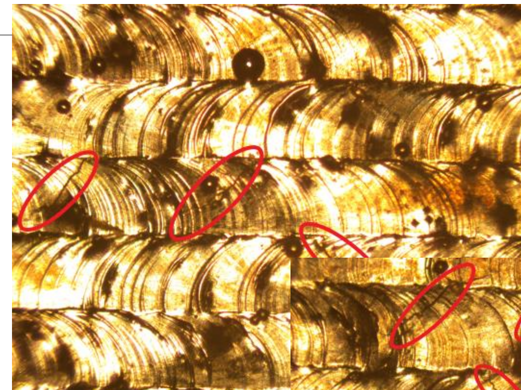
Surface Optical Microscopy (As deposited)

Printing Laser Power

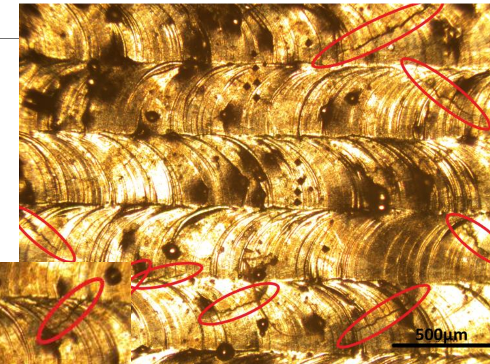
F
Preheat: N/A; Printing: 275 W

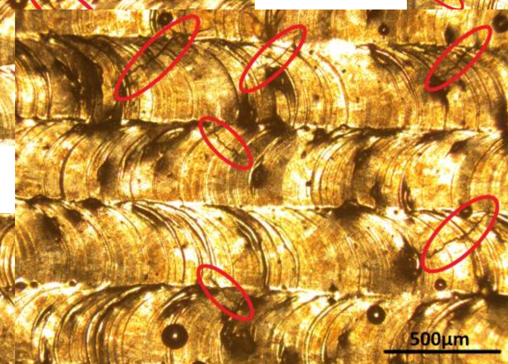


G
Preheat: 300 W; Printing: 275 W

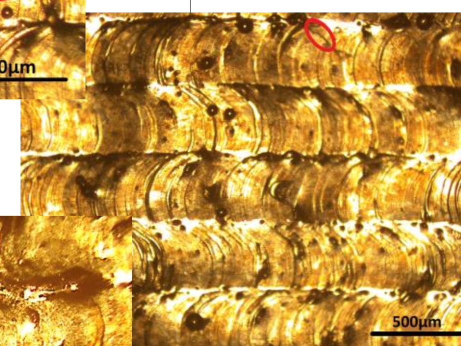


O
Preheat: 400 W; Printing: 275 W)

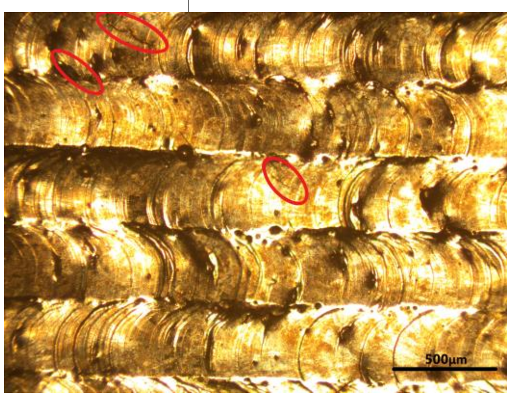




I
Preheat: 350 W;
Printing: 250 W

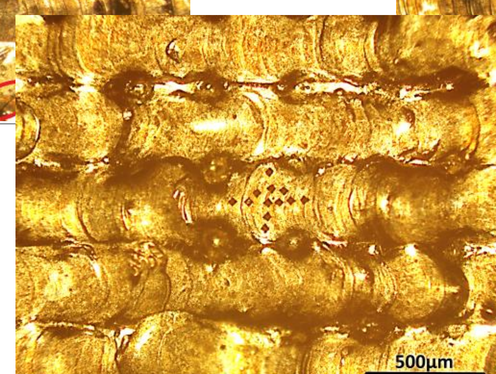


P
Preheat: N/A
Printing: 225 W



B
Preheat: 300 W
Printing: 225 W

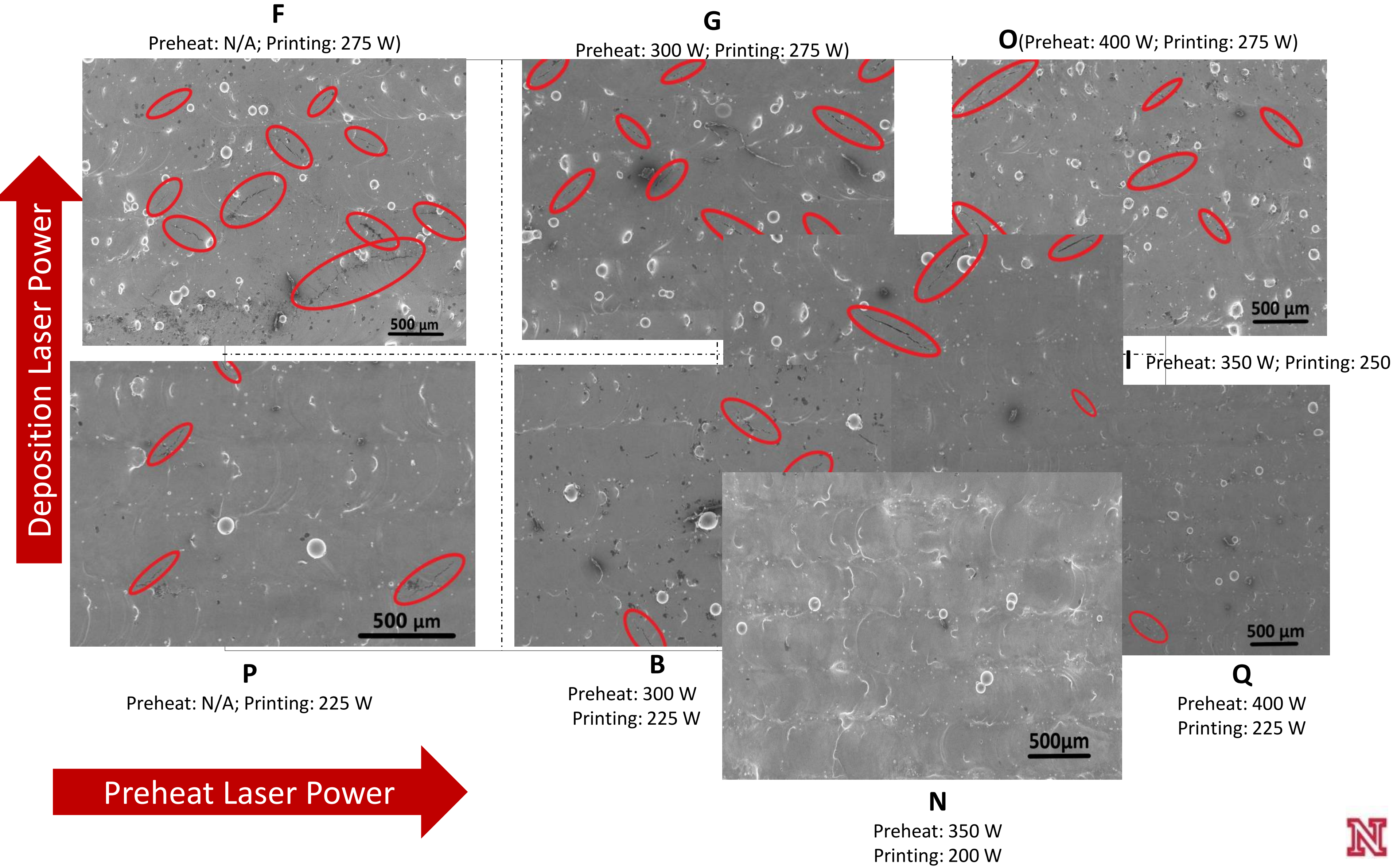
Q
Preheat: 400 W
Printing: 225 W

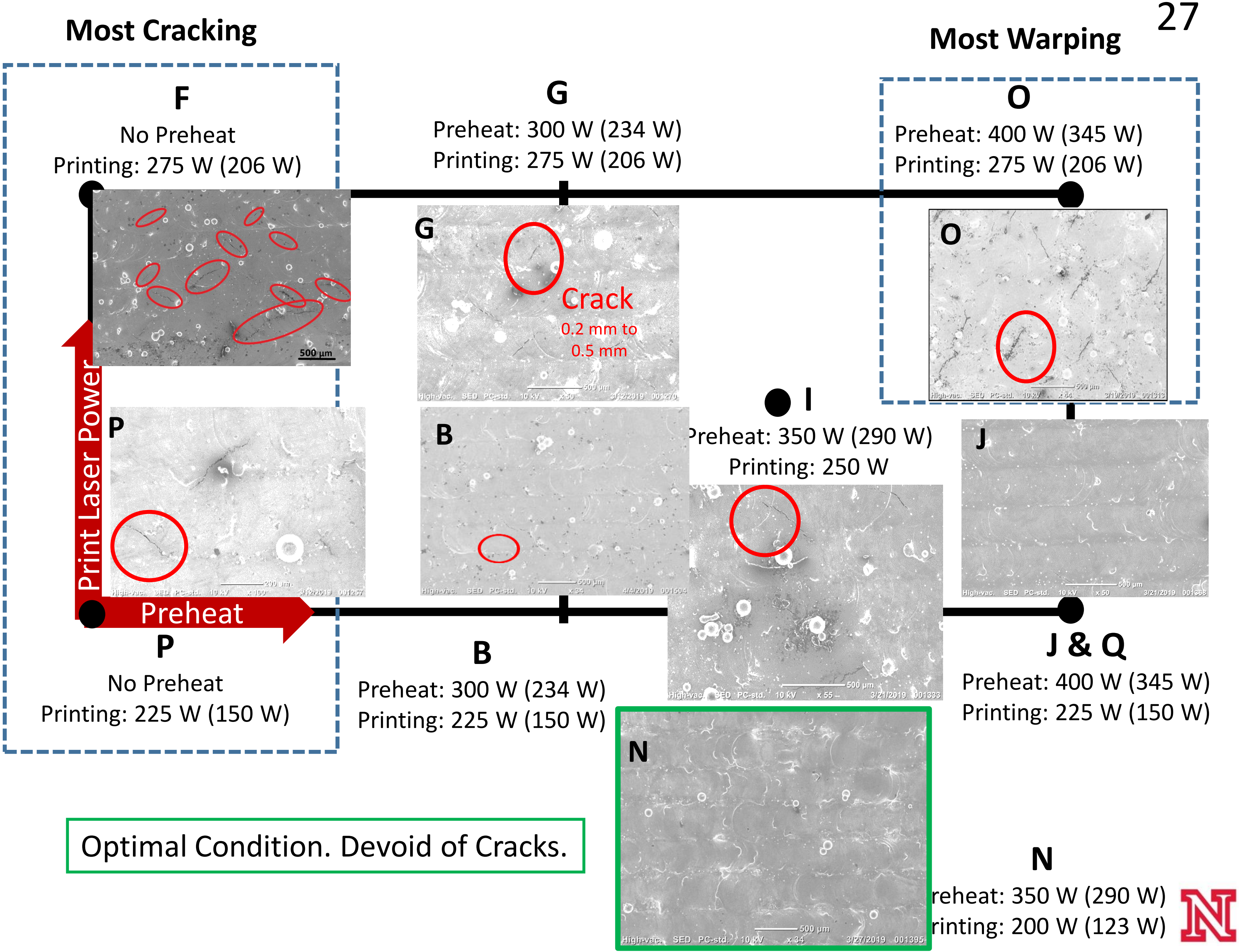


N
Preheat: 350 W
Printing: 200 W

Preheat

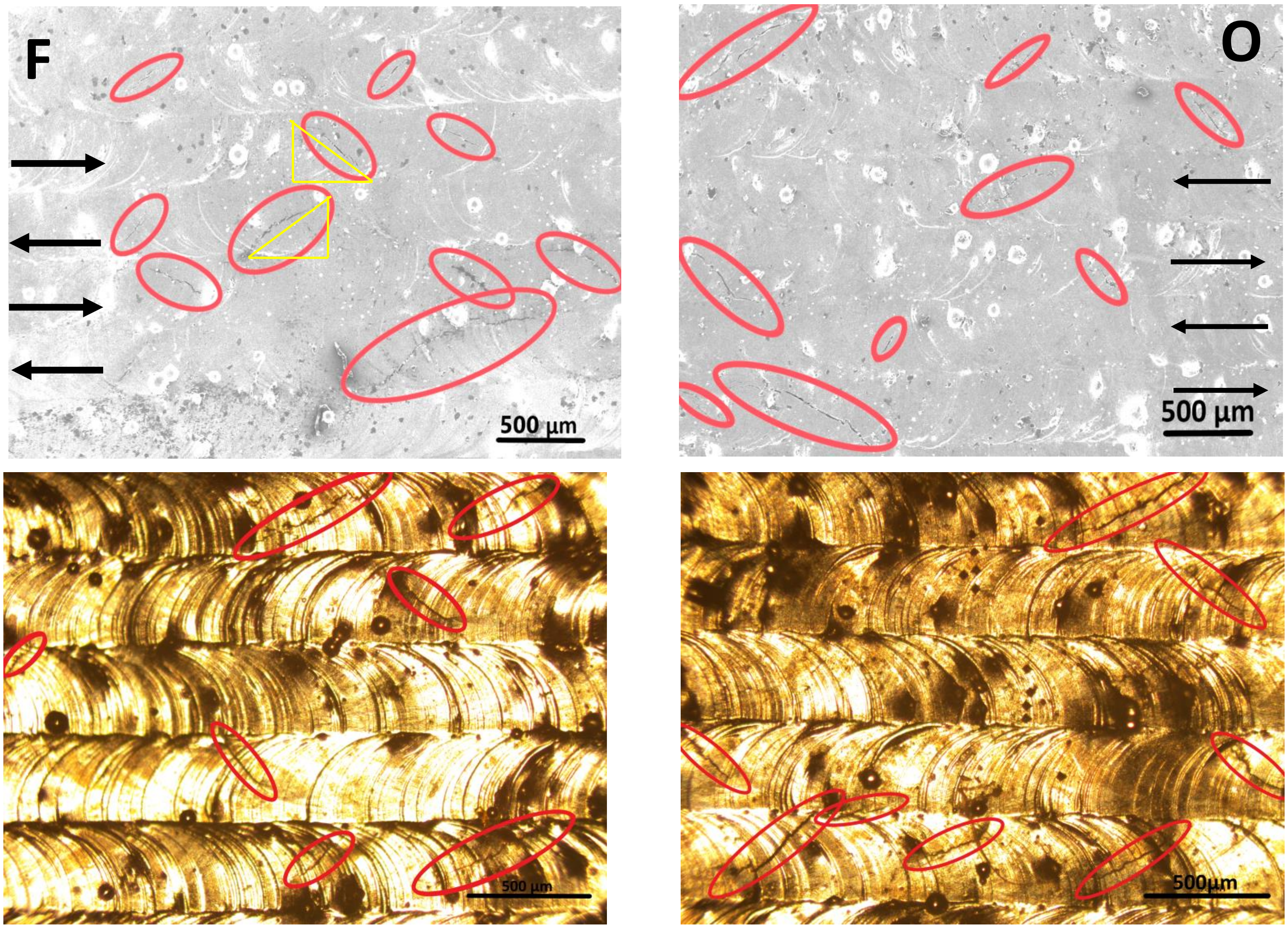
Surface SEM (as-deposited)




Most Cracking
Most Warping
F
No Preheat
Printing: 275 W (206 W)
500 µm
G
Preheat: 300 W (234 W)
Printing: 275 W (206 W)
G
Crack
0.2 mm to
0.5 mm
O
Preheat: 400 W (345 W)
Printing: 275 W (206 W)
O
Print Laser Power
P
B
I
reheat: 350 W (290 W)
Printing: 250 W
J
Preheat
P
No Preheat
Printing: 225 W (150 W)
B
Preheat: 300 W (234 W)
Printing: 225 W (150 W)
J & Q
Preheat: 400 W (345 W)
Printing: 225 W (150 W)
N
N
reheat: 350 W (290 W)
rinting: 200 W (123 W)
Optimal Condition. Devoid of Cracks.

Cracking is related to the scanning direction

F
No Preheat
Printing: 275 W (206 W)



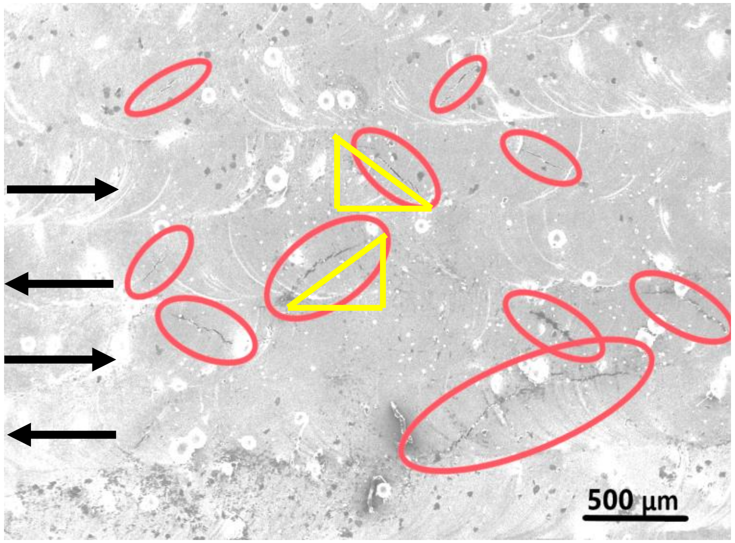
O
Preheat: 400 W (345 W)
Printing: 275 W (206 W)

Cracks cross the scan vector at nearly 45°

F

No Preheat

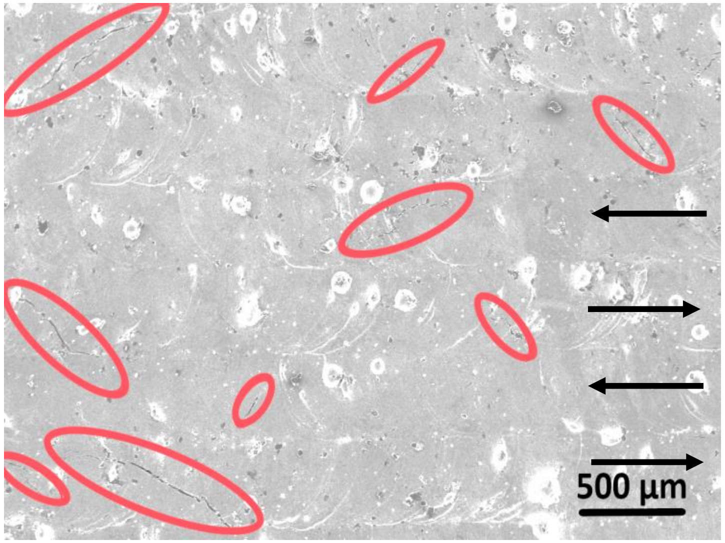
Printing: 275 W (206 W)

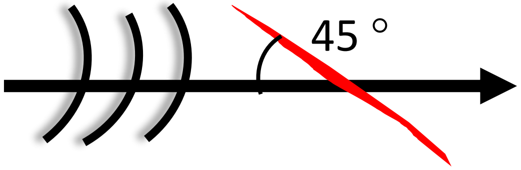


O

Preheat: 400 W (345 W)

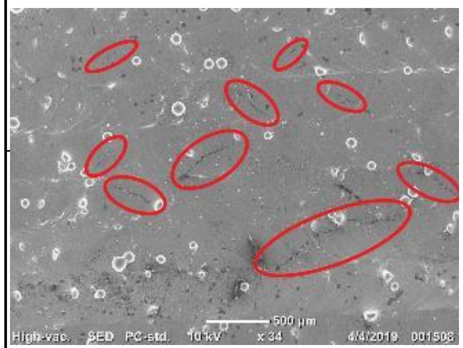
Printing: 275 W (206 W)





Samples Chosen for Microstructural Characterization

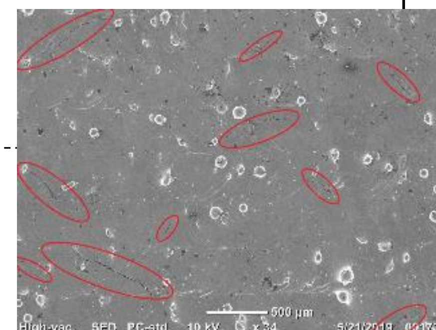
F
Preheat: N/A
Printing: 275 W
Sample 4



Scale bars= 500 µm

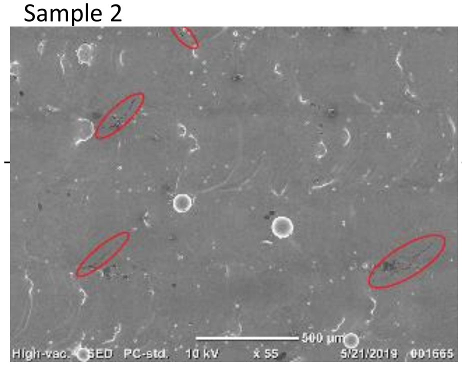
G
Preheat: 300 W)
Printing: 275 W
Sample 3

O
Preheat: 400 W
Printing: 275 W
Sample 8

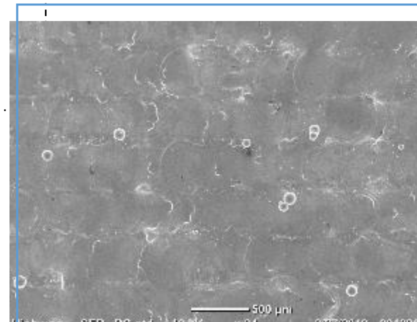


I
Preheat: 350 W
Printing: 250 W
Sample 7

P
Preheat: N/A
Printing: 225 W
Sample 2

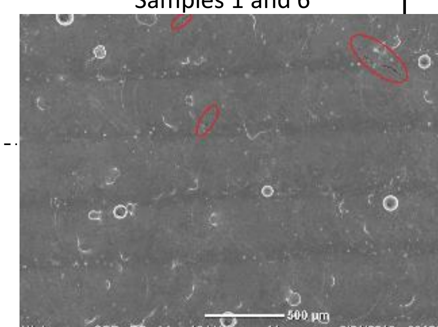


B
Preheat: 300 W
Printing: 225 W
Sample 5



N
Preheat: 350 W
Printing: 200 W
Sample 9

Q
Preheat: 400 W
Printing: 225 W
Samples 1 and 6

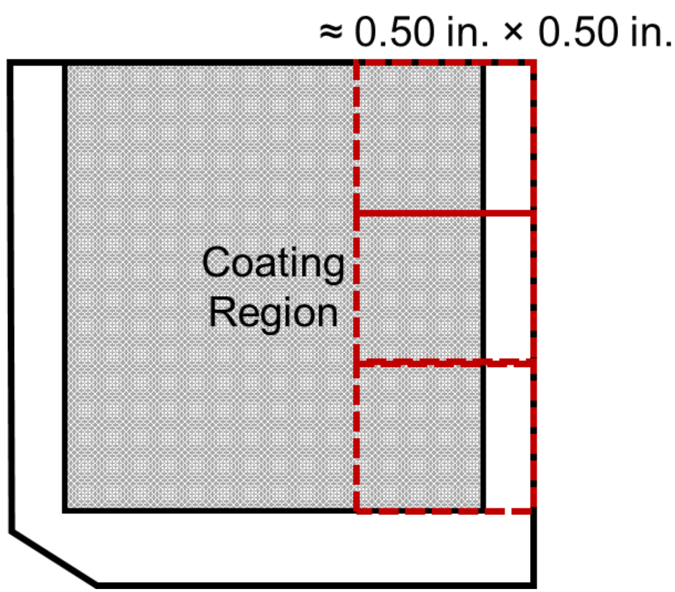


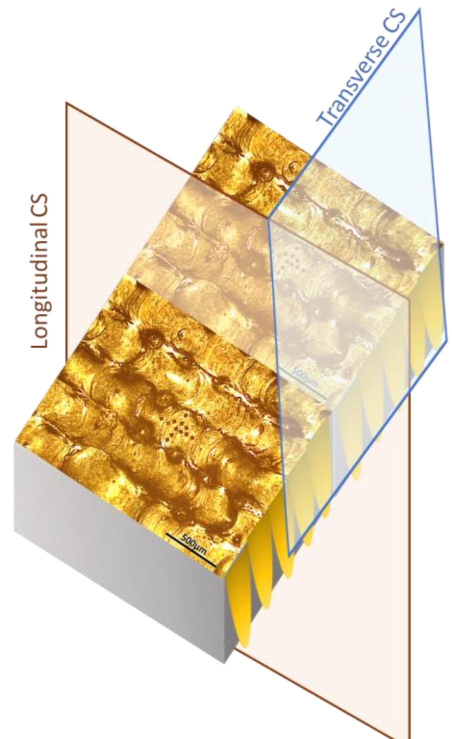
DepositionLaser Power

Preheat Power

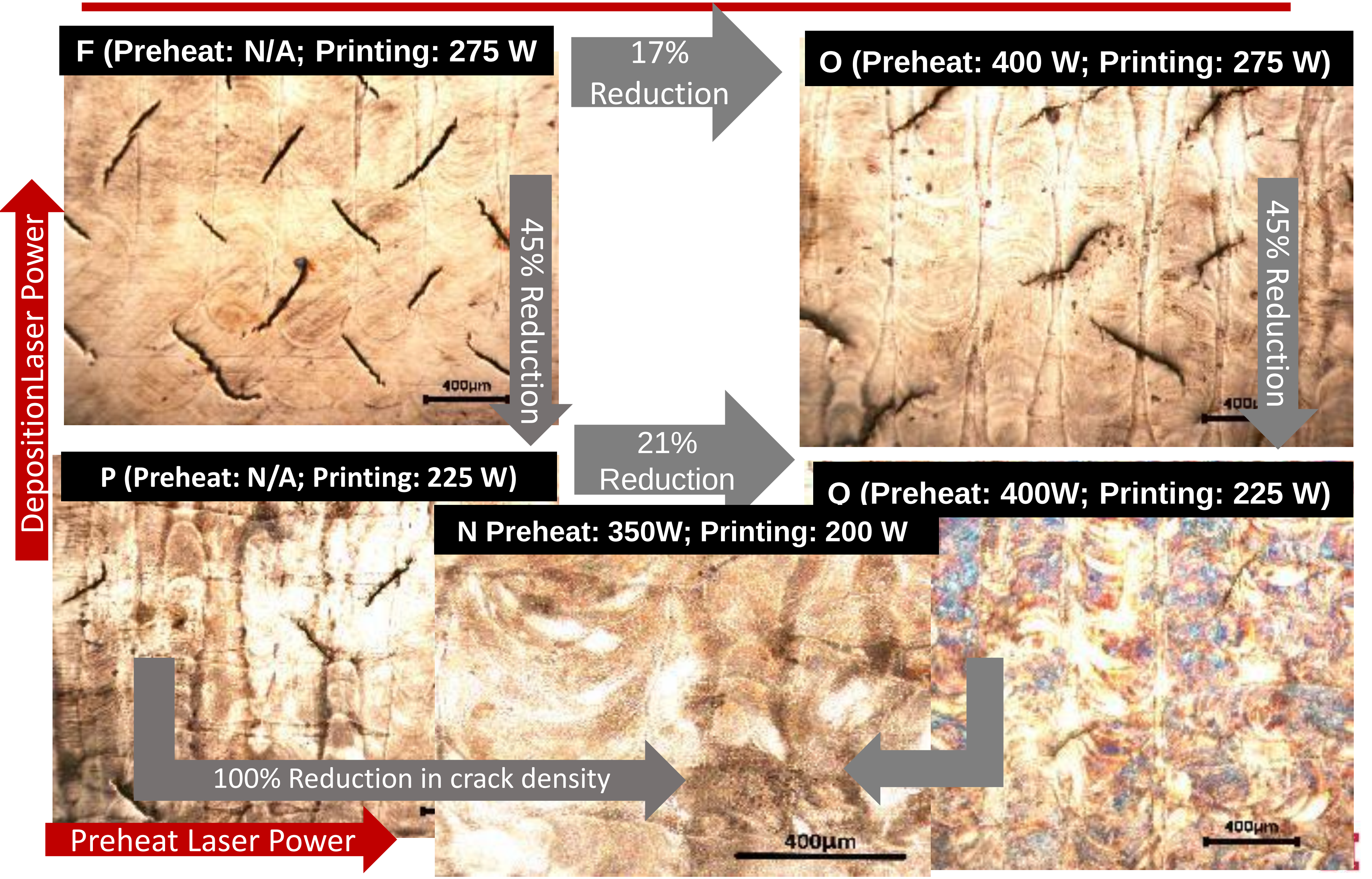
Sample Preparation

- Small samples $\approx$ 0.5 inch X 0.5 inch were cut by EDM
- Top surface, and exposed cross sections of the coating were ground mechanically using 400, 600, 800, and 1200 grit SiC sandpaper.
- Polished using diamond paste (3, 1, and 0.5 microns)
- Etched with aqua regia ($HCL:HNO_3$=3:1)

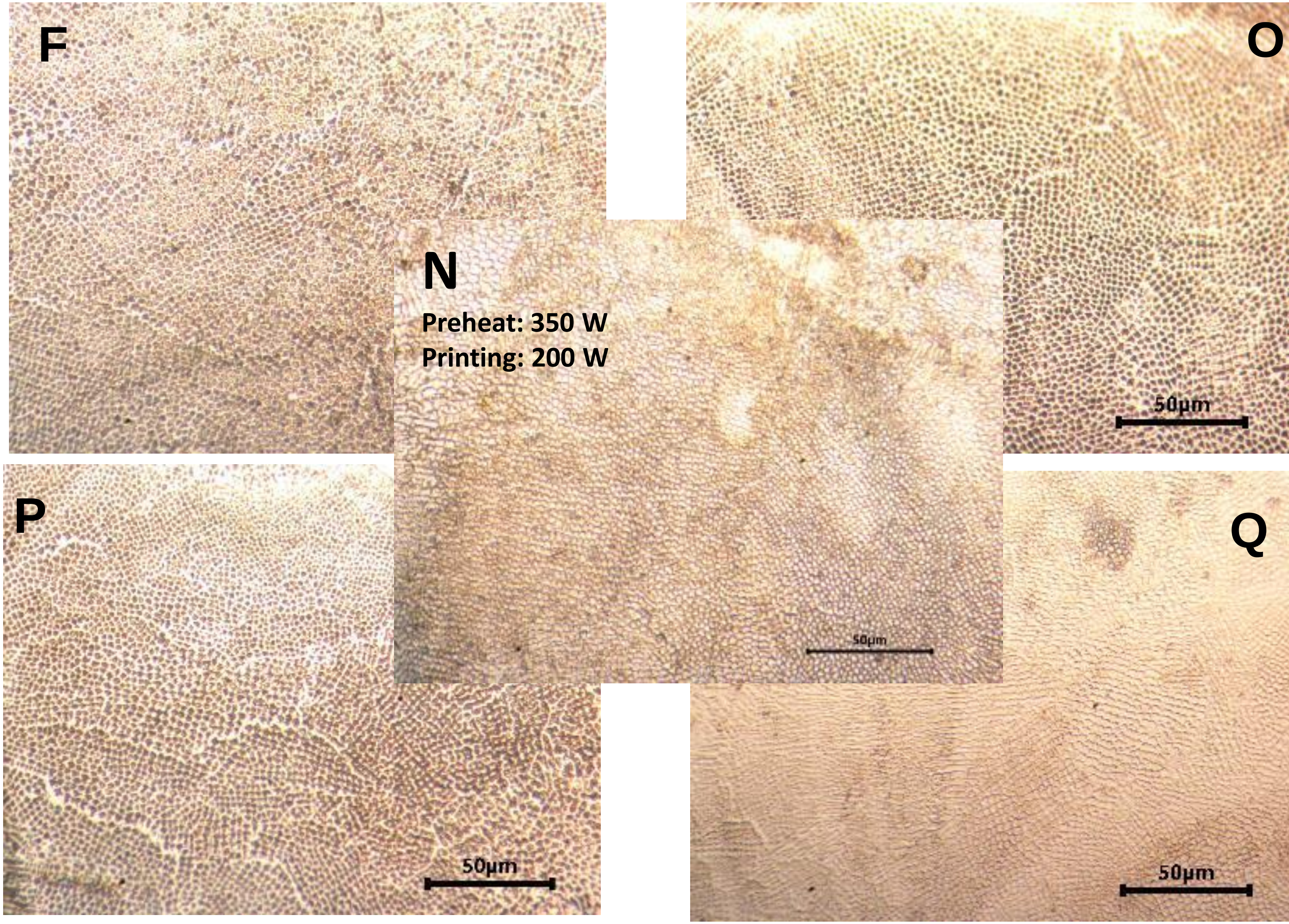




Effect of Preheat and Deposition Laser Power on Crack Density



Dendritic microstructure observed on the surface as function of preheat & deposition laser power



F Preheat: N/A Printing: 275 W

O Preheat: 400 W Printing: 275 W

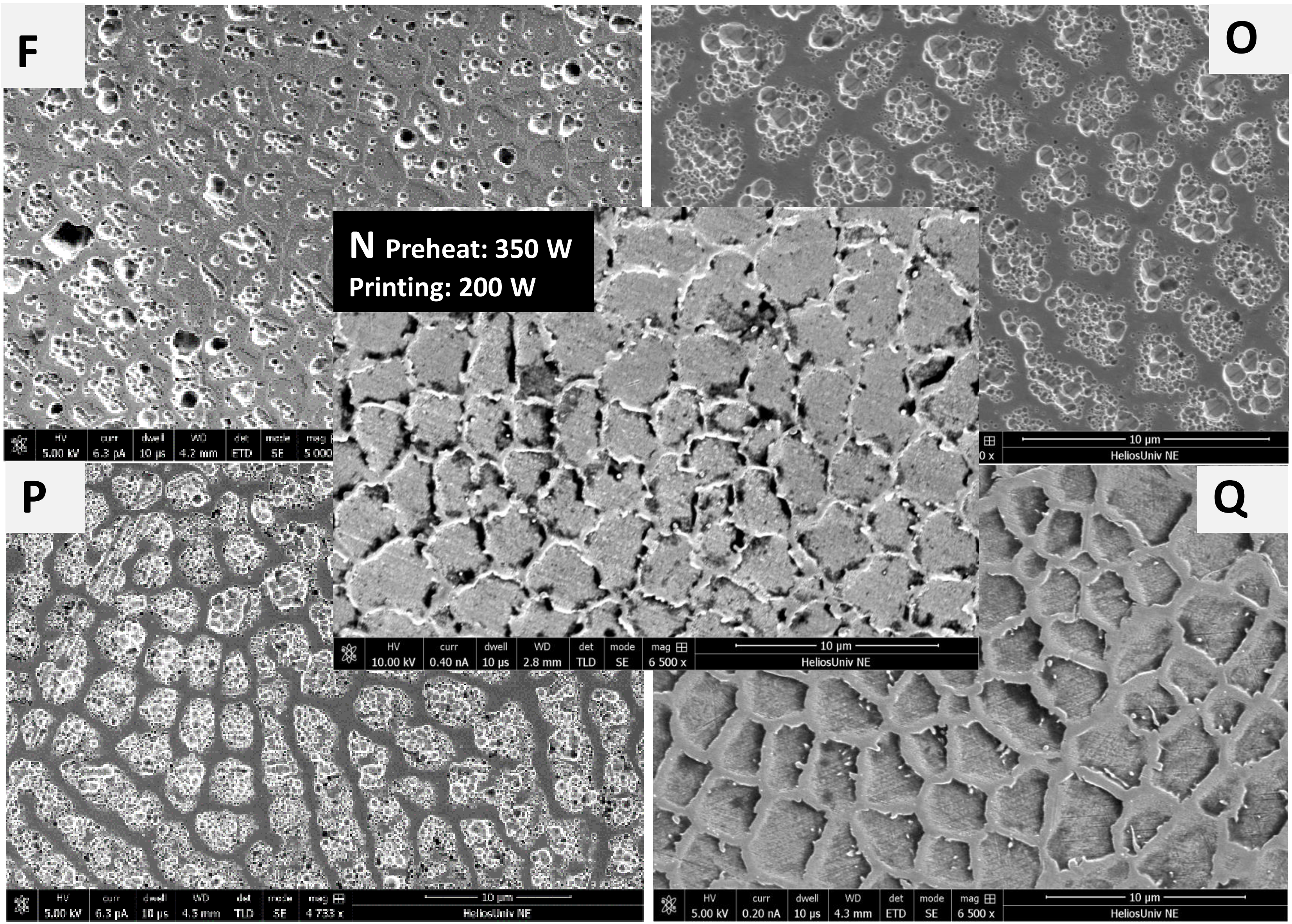
P Preheat: N/A Printing: 225 W

Q Preheat: 400 W Printing: 225 W

Surface Microstructure under SEM

F Preheat: N/A Printing: 275 W

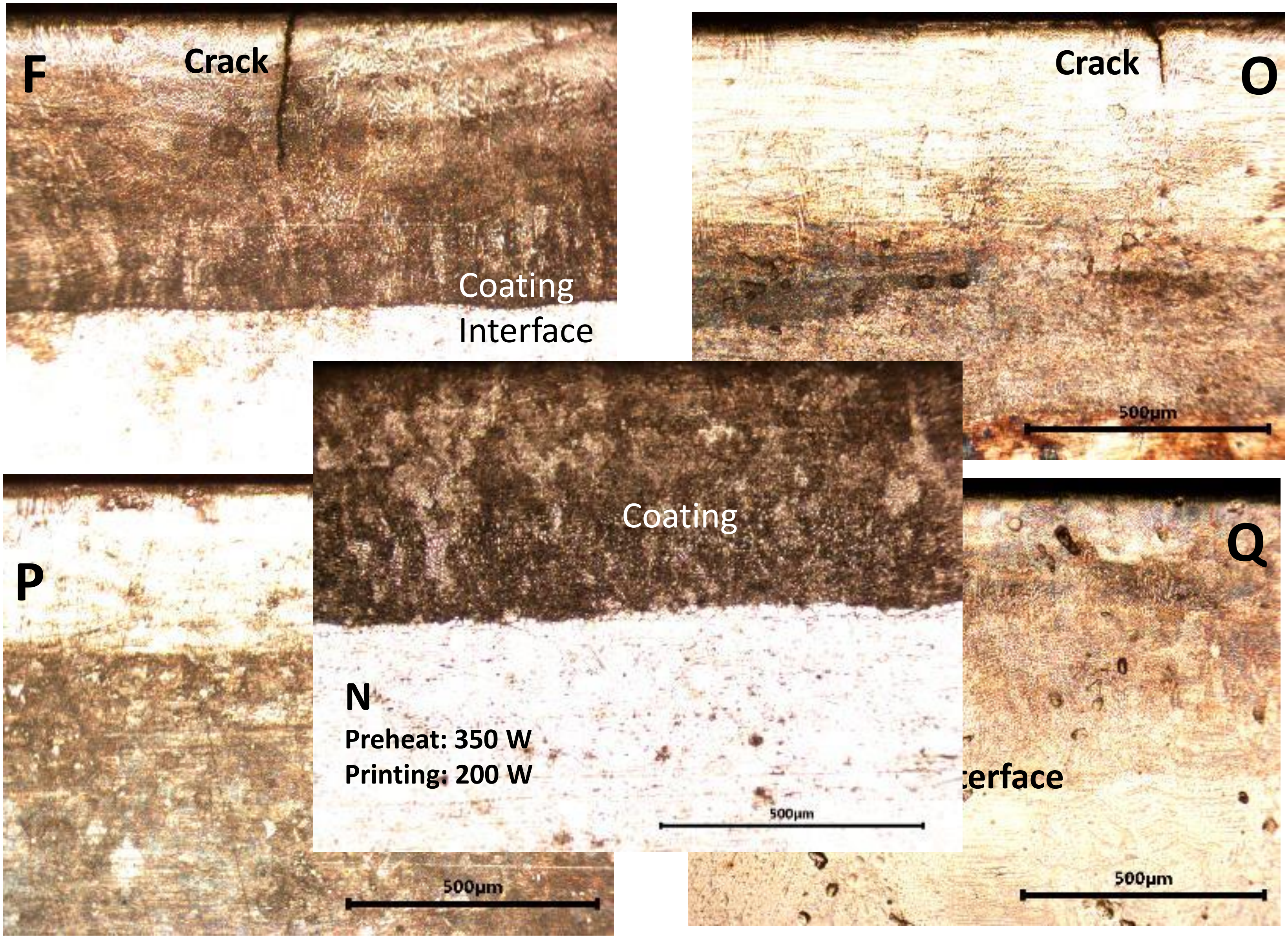
O Preheat: 400 W Printing: 275 W



P Preheat: N/A Printing: 225 W

Q Preheat: 400 W Printing: 225 W

Longitudinal cross-section
Cracks penetrate as much as 100 – 500 µm into the coating



F Preheat: N/A Printing: 275 W

O Preheat: 400 W Printing: 275 W

P Preheat: N/A Printing: 225 W

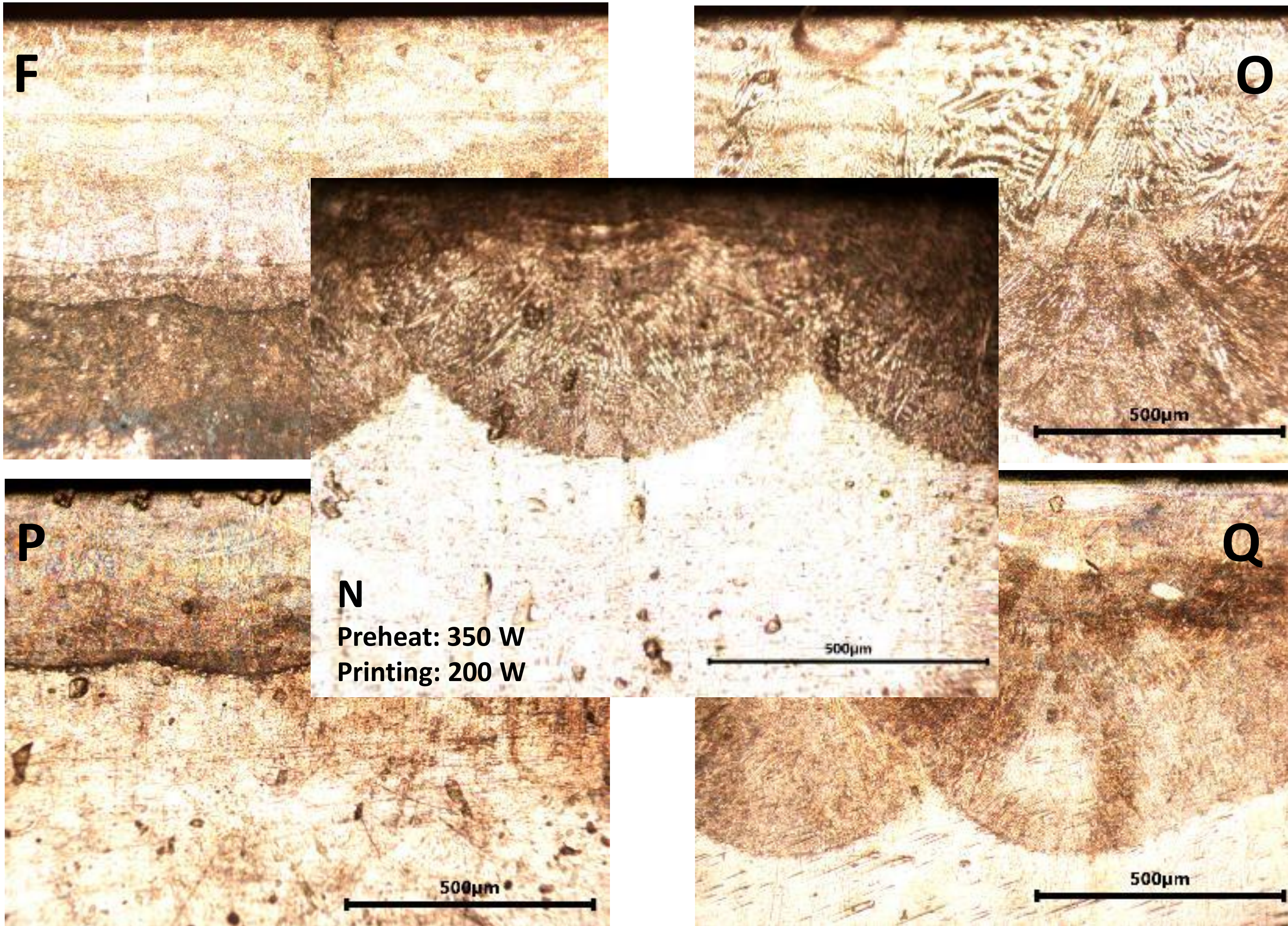
Q Preheat: 400 W Printing: 225 W

Transverse cross-section

Penetration of the coating into the substrate increases with preheat and deposition laser power

F Preheat: N/A Printing: 275 W

O Preheat: 400 W Printing: 275 W

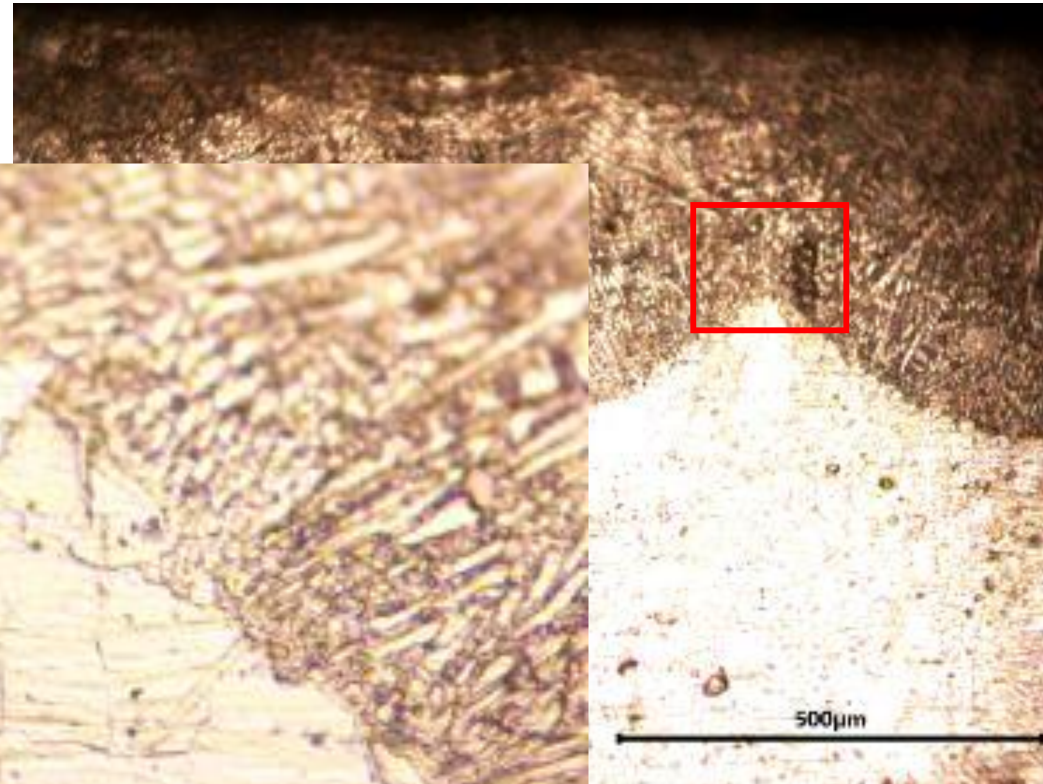


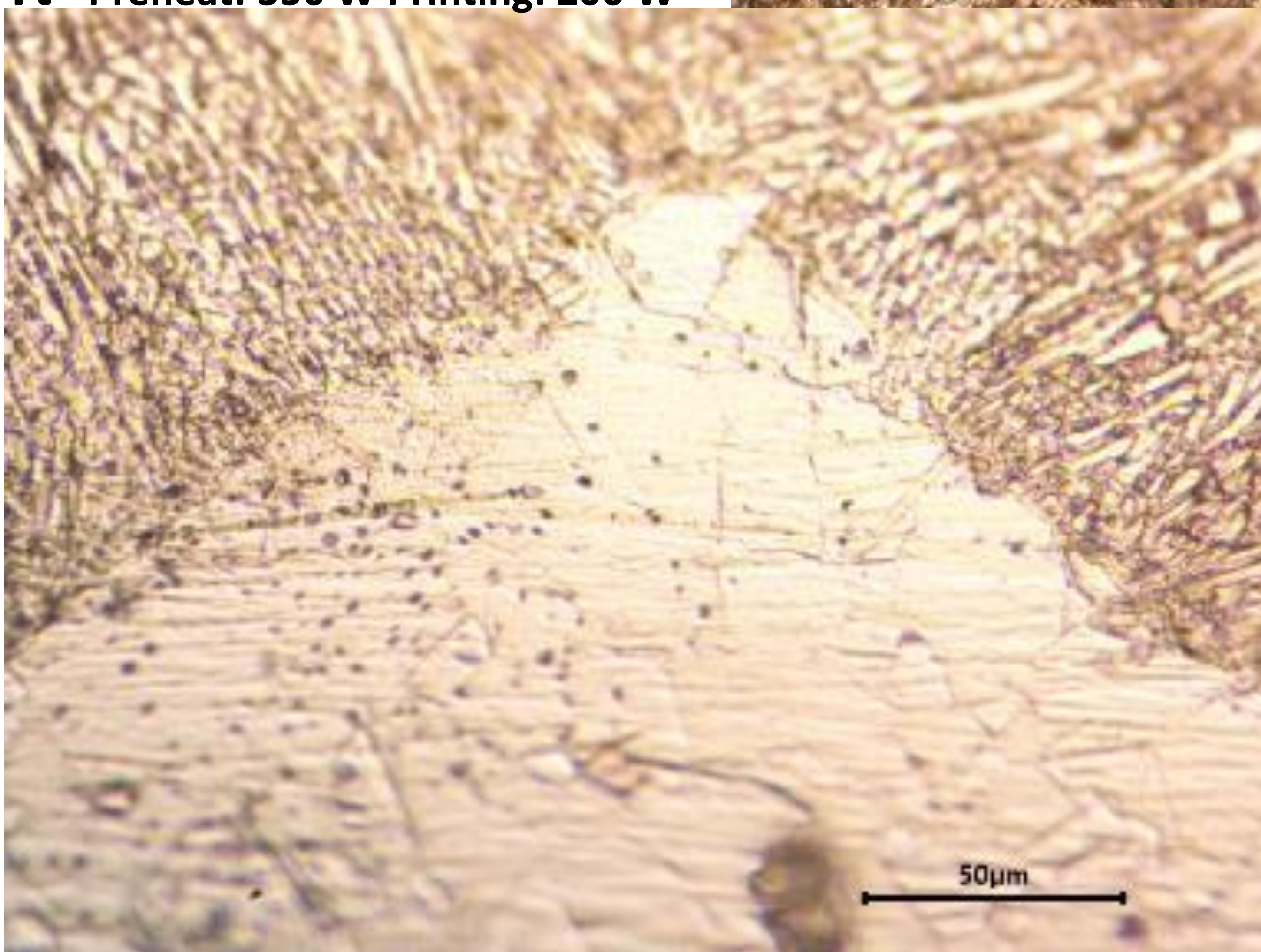
P Preheat: N/A Printing: 225 W

Q Preheat: 400 W Printing: 225 W

Surface and Cross-sectional Microstructure

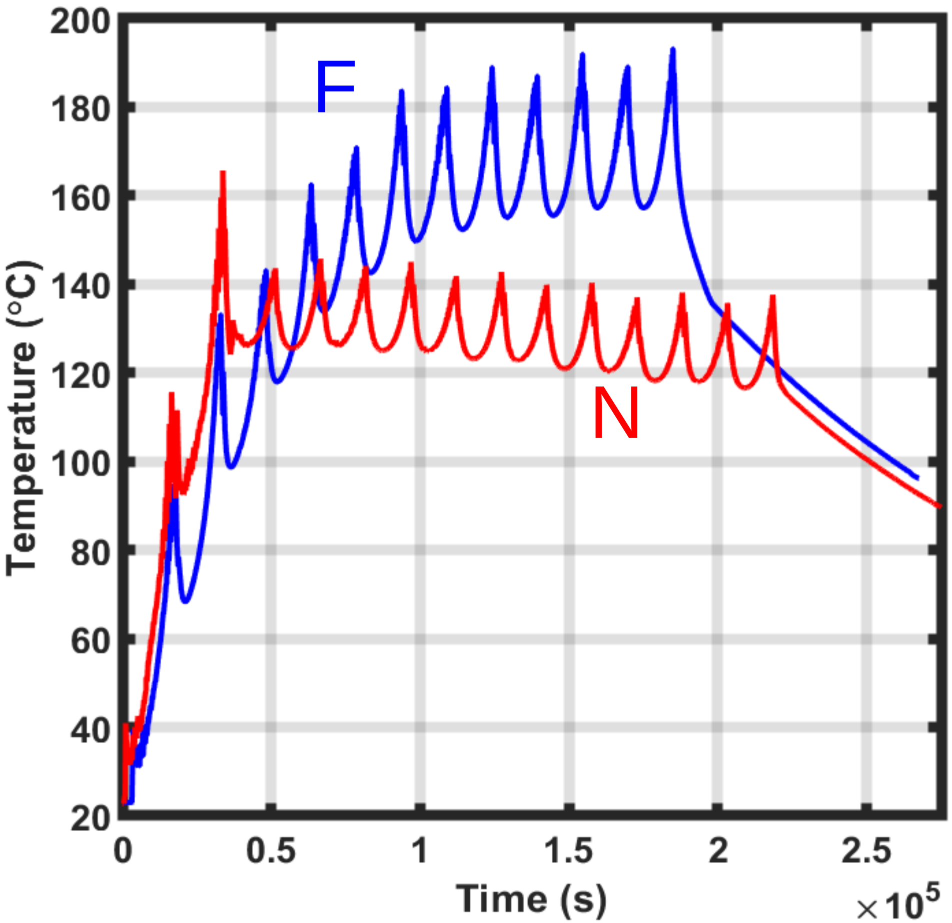
N **Preheat: 350 W Printing: 200 W**

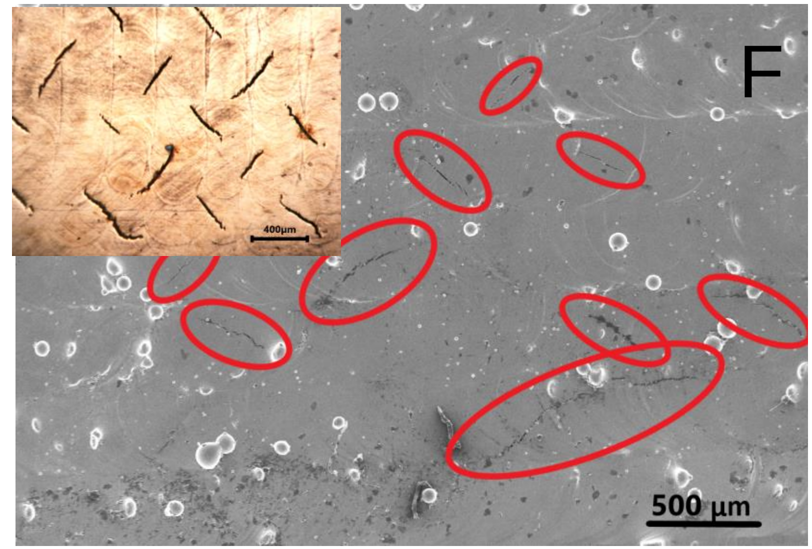




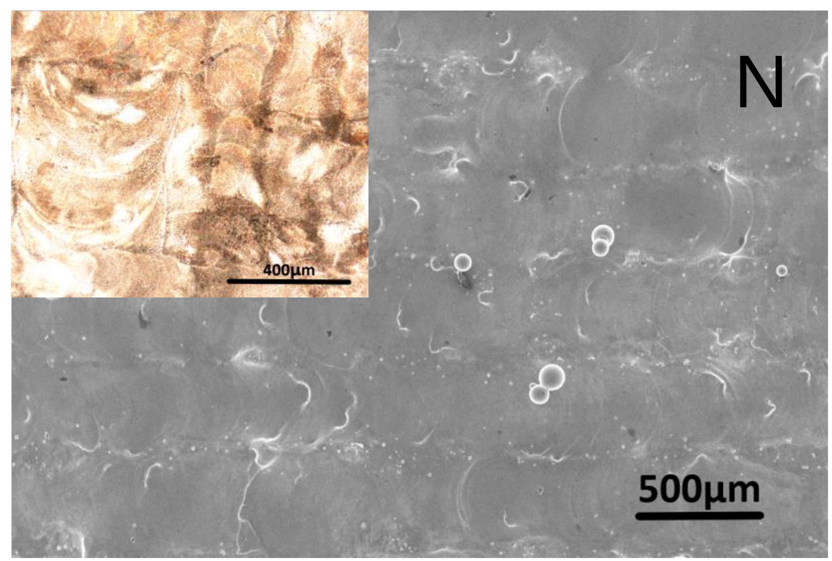
Hypothesis

Preheating and low deposition power lead to smaller thermal gradients, and hence minimize cracking.





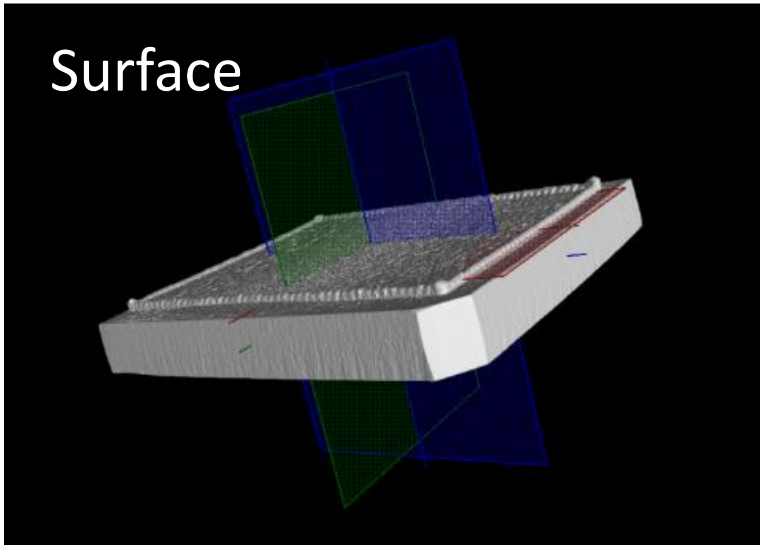
F (Preheat: N/A; Printing: 275 W)

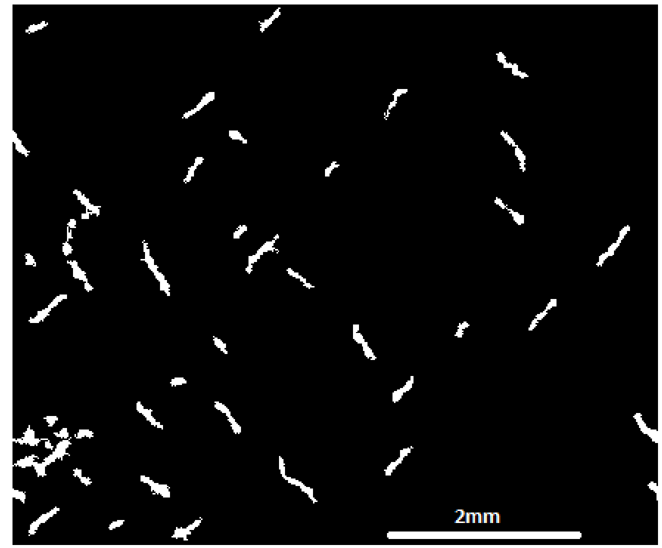


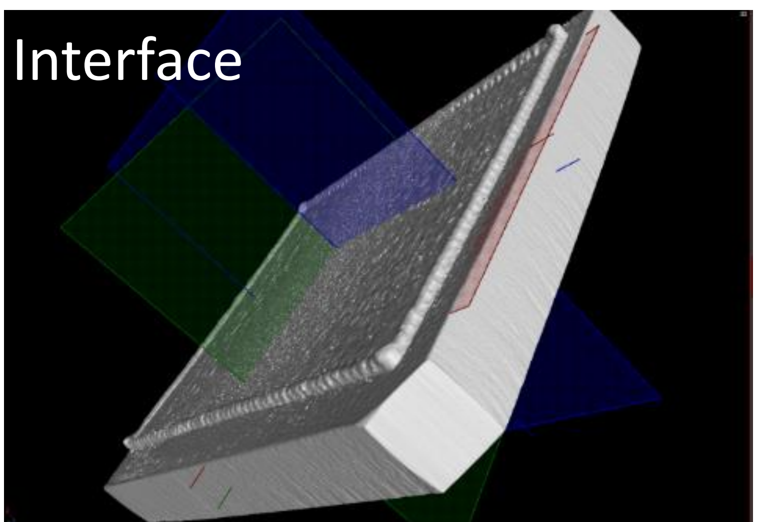
N (Preheat: 350; Printing: 200 W)

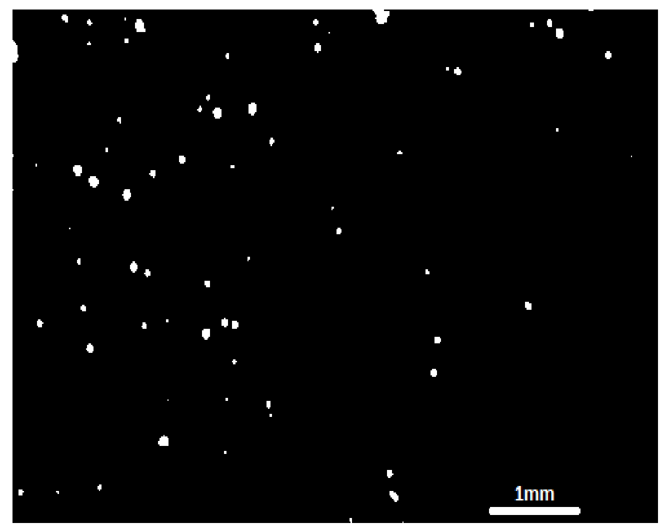
X-Ray CT analysis of Surface and Interface

F Preheat: N/A Printing: 275 W







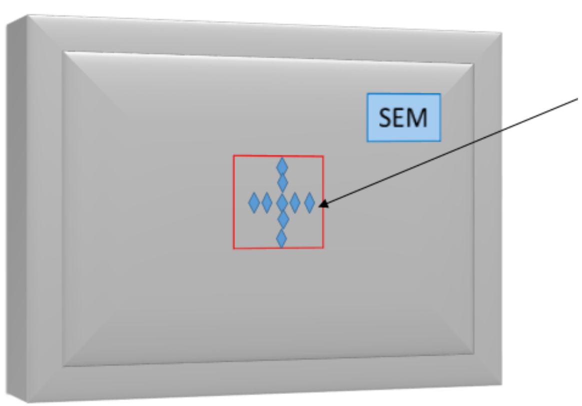


Outline

- Background and Prior Work
- Methods
  - Experimental Plan & Setup
  - Instrumentation of Sensor Array
- Results
  - Microstructure characterization (Optical, XCT, SEM)
  - Hardness testing
- Summary & Future Work

Surface Hardness Testing

Sample	Preheat	Preheat Laser (W)	Print Laser (W)	Remarks	Mean Hardness (HV)	Hardness σ
P	N	-	225	High Cracking	435.4	47.5
G	Y	300	275		427.8	26.7
F	N	-	275	High Cracking	430.4	28.4
B	Y	300	225	Less Cracking	419.4	24.5
O	Y	400	275	High Warping	410	35.2
I	Y	350	250		398.5	34.2
J	Y	400	225	Less Cracking	438.4	16.9
Q	Y	400	225	Less Cracking	541.8	39.9
N	Y	350	200	Least Cracking	428.2	17.7



Vickers Hardness at 9 points

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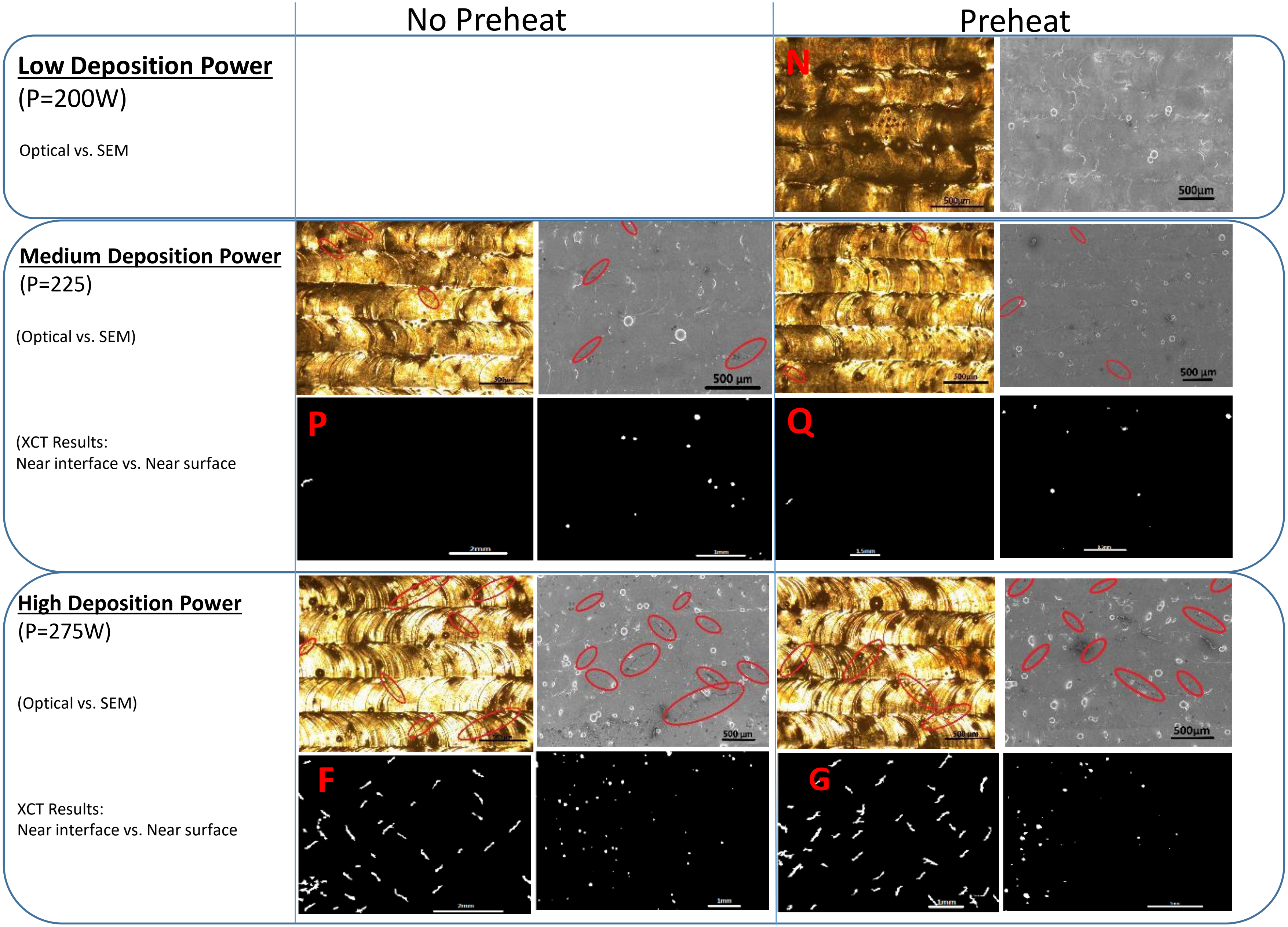
No Preheat
Preheat
Low Deposition Power
(P=200W)
Optical vs. SEM
N
500µm
Medium Deposition Power
(P=225)
(Optical vs. SEM)
(XCT Results:
Near interface vs. Near surface
500 µm
500 µm
P
Q
2mm
High Deposition Power
(P=275W)
(Optical vs. SEM)
XCT Results:
Near interface vs. Near surface
500 µm
500µm
F
G
1mm

Ongoing Work

1. EDS to characterize change in elemental composition
2. Mechanical characterization (wear and 3-point bending)
3. Modeling and In-process Data Analytics