Influence of High-Intensity Ultrasound on Ti-6Al-4V Microstructure During Laser Powder Bed Fusion Solidification Conditions

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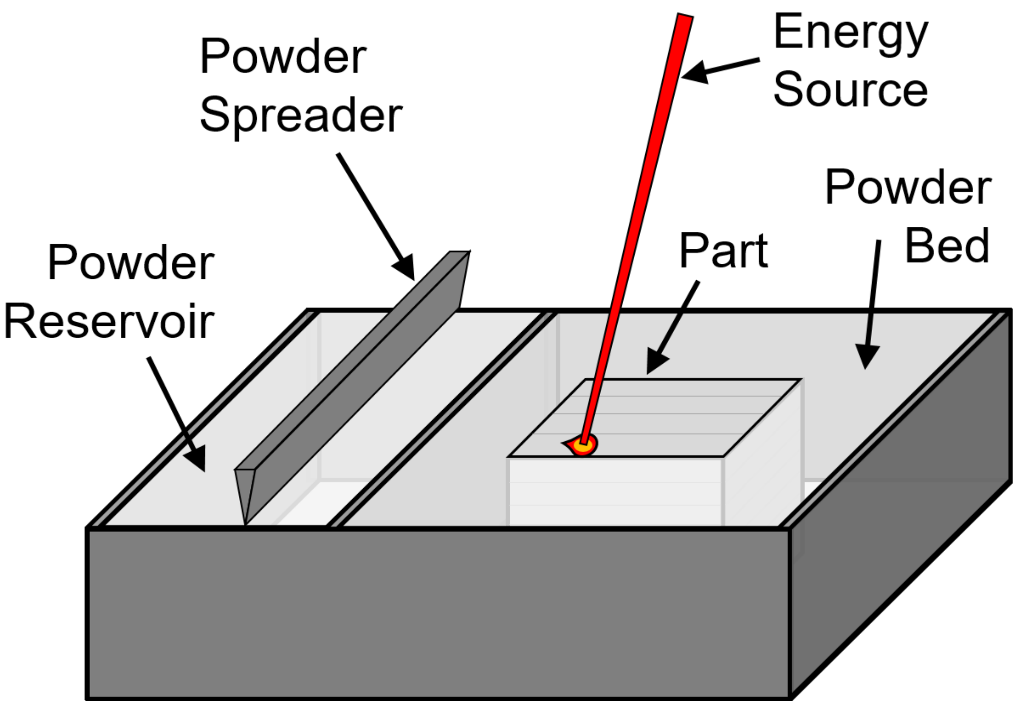
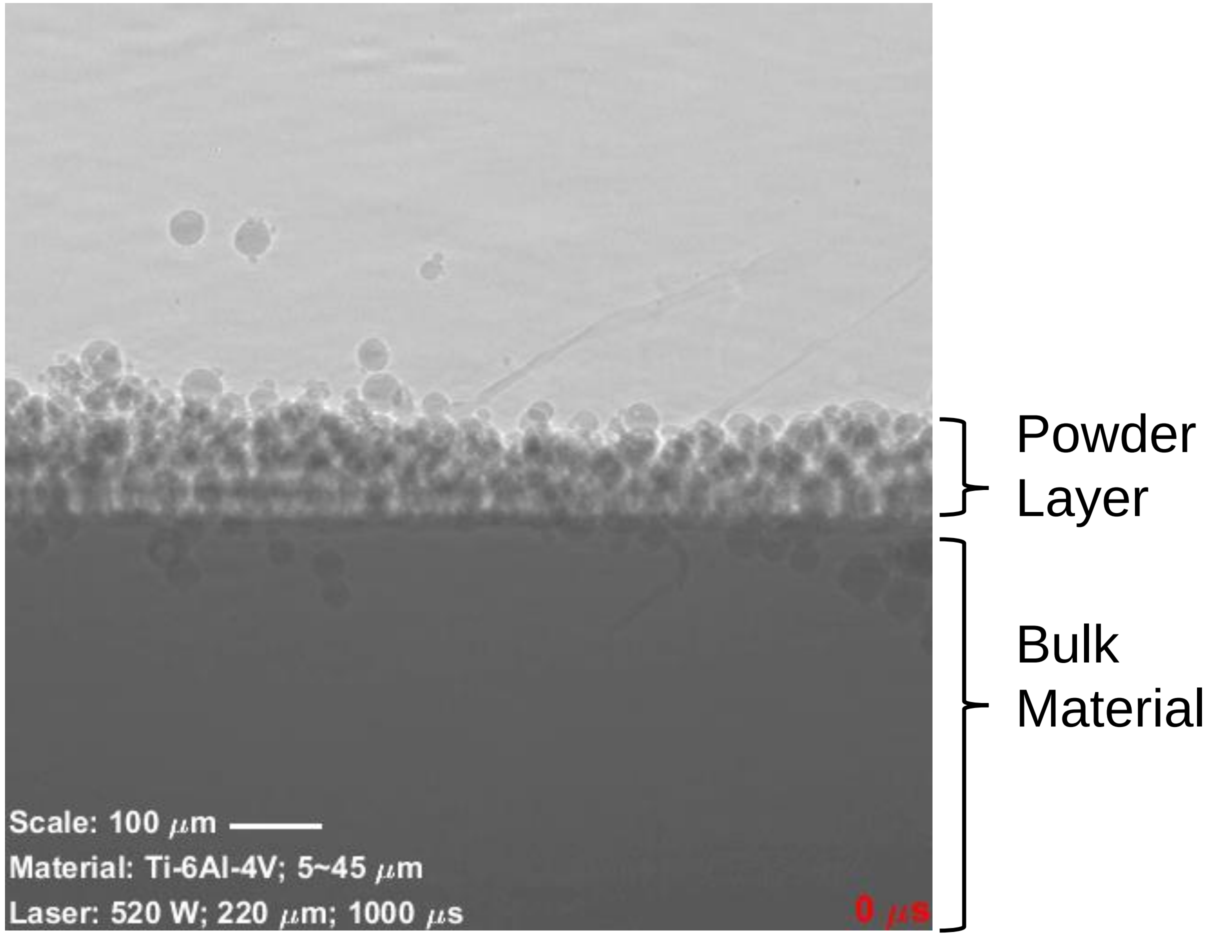
Powder Bed Fusion Additive Manufacturing

- Spread powder, melt, & repeat…

Diagram of Powder Bed Fusion (PBF)



[1] Solidification Dynamics of the PBF Process

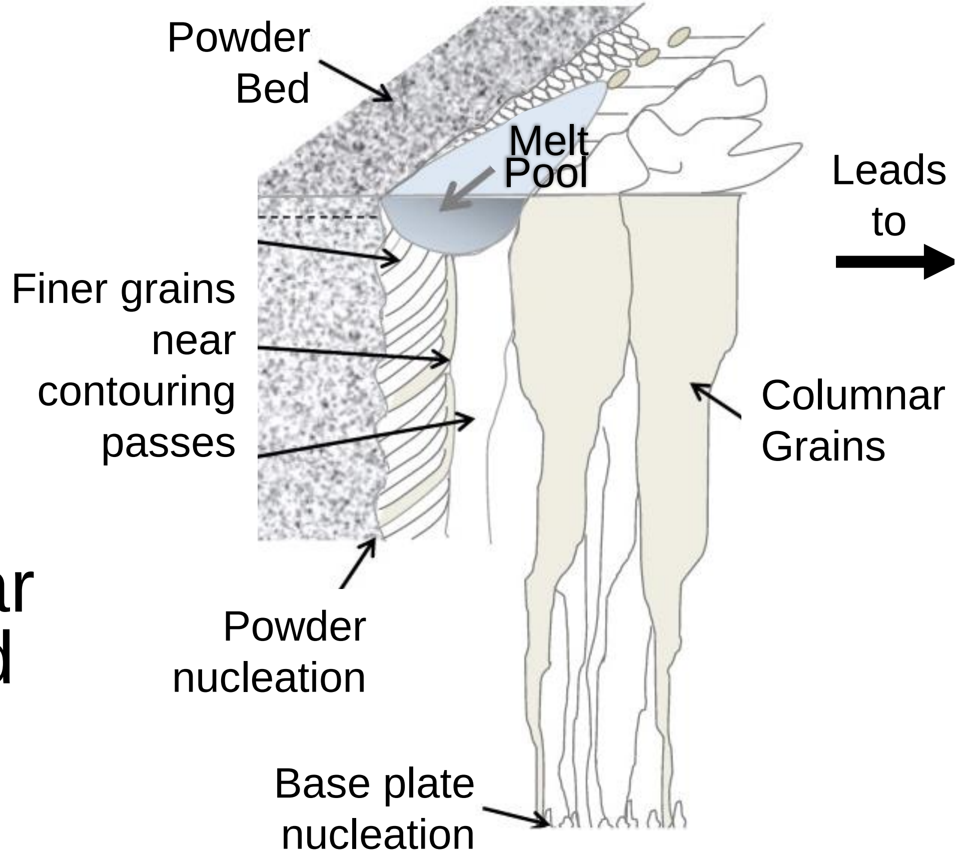


[1] C. Zhao, *et al.*, "Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction." Sci Rep 7, 3602 (2017), https://doi.org/10.1038/s41598-017-03761-2

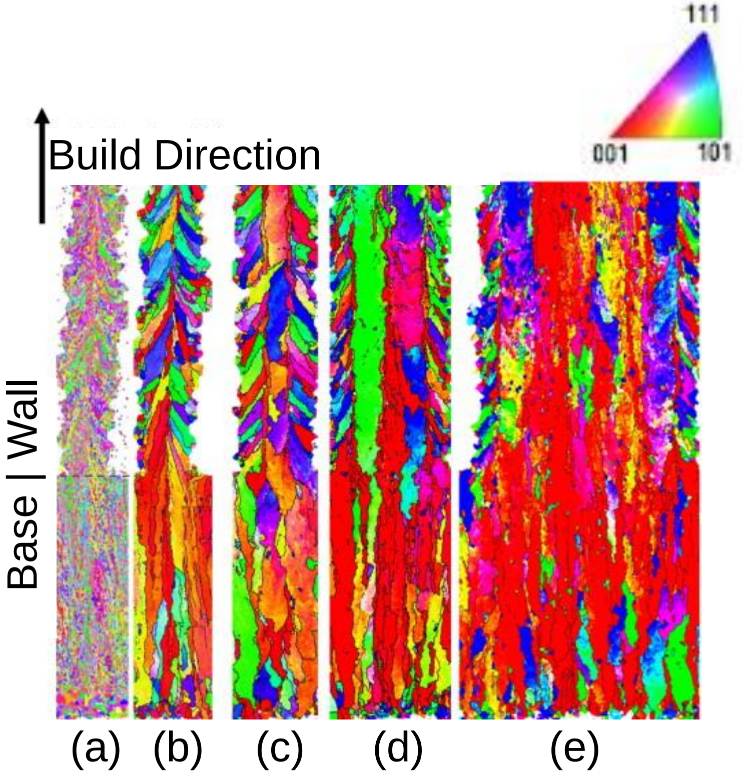
Microstructure developing during PBF

- Repeated melting and solidification events

- Causes the formation of large, columnar grains oriented in the build direction



[2] Microstructure Development Mechanism

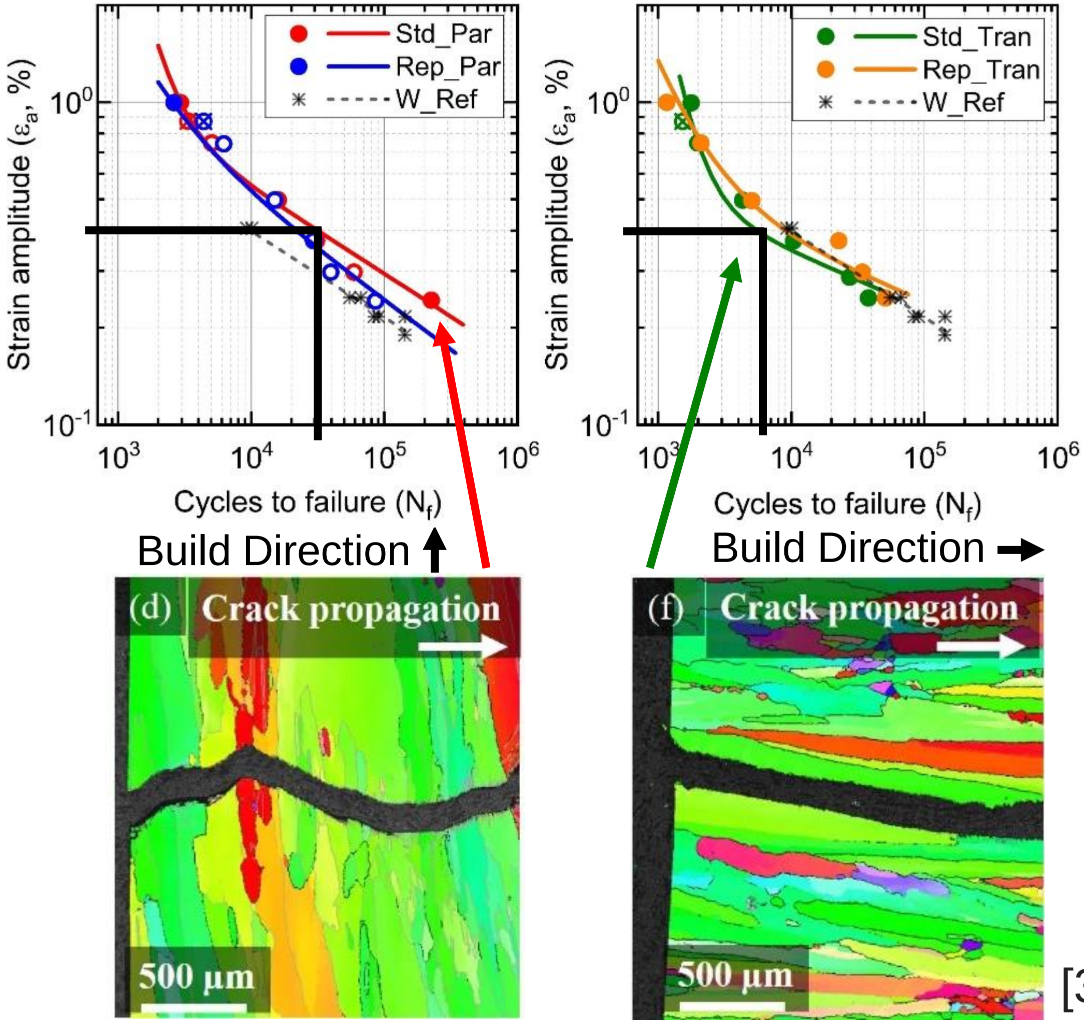


[2] Examples of reconstructed β-grain structures for (b) 1 mm, (c) 1.5 mm, (d) 2.0 mm, and (e) 5 mm wide walls in Ti64

[2] A.A. Antonysamy et al., "Effect of build geometry on the β-grain structure and texture in additive manufacture of Ti6Al4V by selective electron beam melting." *Materials characterization* 84 (2013): 153-168., https://doi.org/10.1016/j.matchar.2013.07.012

AM Microstructure – Why is it important?

- ❖ Columnar grains cause location-dependent variability in properties
- ❖ Makes qualification and certification (Q&C) of aerospace parts difficult
- ❖ What can be done to refine/prevent this microstructure?



[3]

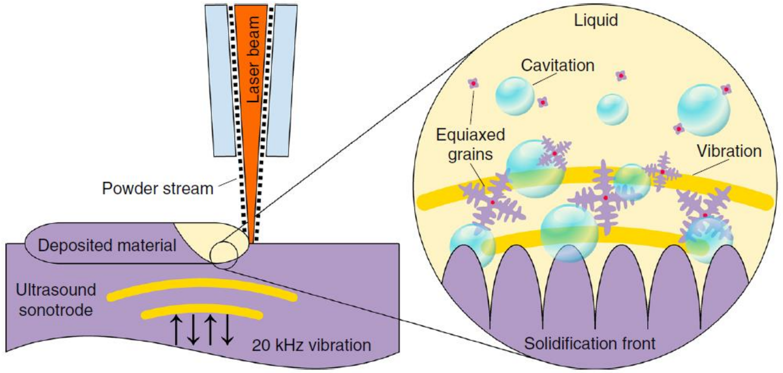
[3]

[3] A.R. Balachandramurthi, "Anisotropic fatigue properties of Alloy 718 manufactured by Electron Beam Powder Bed Fusion," Int. J. Fatigue 141 (2020)

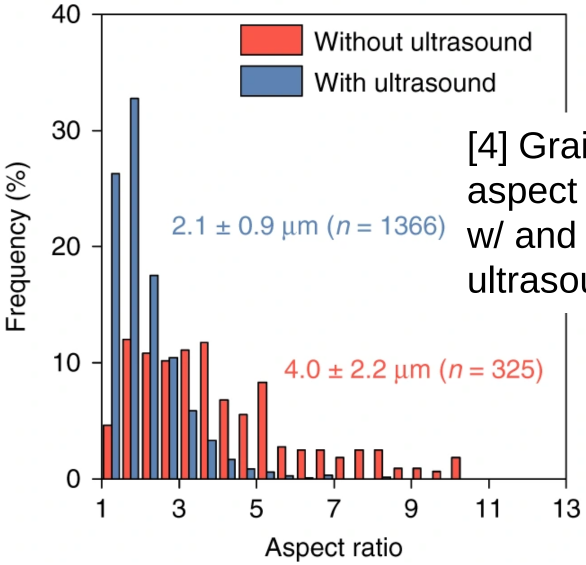
https://doi.org/10.1016/j.ijfatigue.2020.105898
Figures cropped, re-arranged, and lines added vs. original

Ultrasonic-Induced Grain Refinement

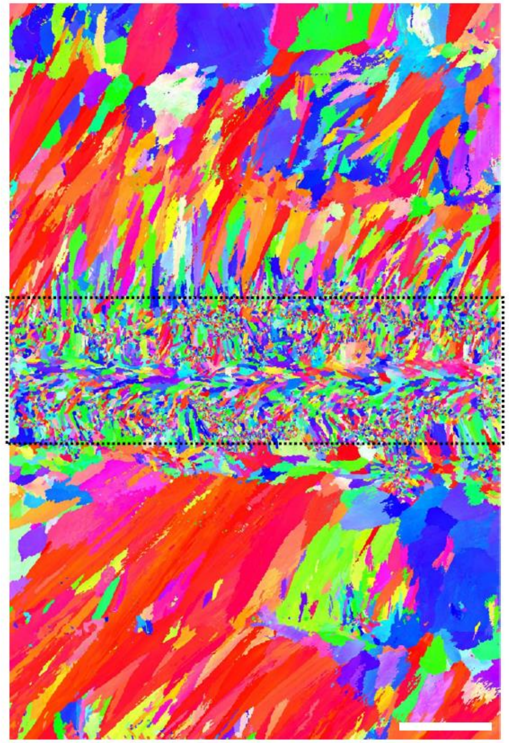
- Recent work has demonstrated the viability of ultrasonic (US) cavitation for in-situ microstructure refinement during AM of alloy Ti-6Al-4V [4]
- Limited to Directed-Energy-Deposition (DED) Processing
- Is this compatible with PBF?



[4] Ultrasonic Cavitation Grain Refinement Mechanism



[4] Grain aspect ratio w/ and w/o ultrasound



US Off

US On

US Off

[4] Inconel 625 w/ and w/o ultrasound

[4] C.J. Todaro et al., "Grain structure control during metal 3D printing by high-intensity ultrasound." *Nature communications* 11.1 (2020): 1-9. https://doi.org/10.1038/s41467-019-13874-z

Overview and Objective of Current Work

- ❖ Three linked research areas

- ❖ Objective is to test feasibility of using ultrasonic induced grain refinement for PBF

<u>Thermal Simulations of the DED & PBF Processes</u>
- What temp. gradients are imposed?
- What is the solidification rate?

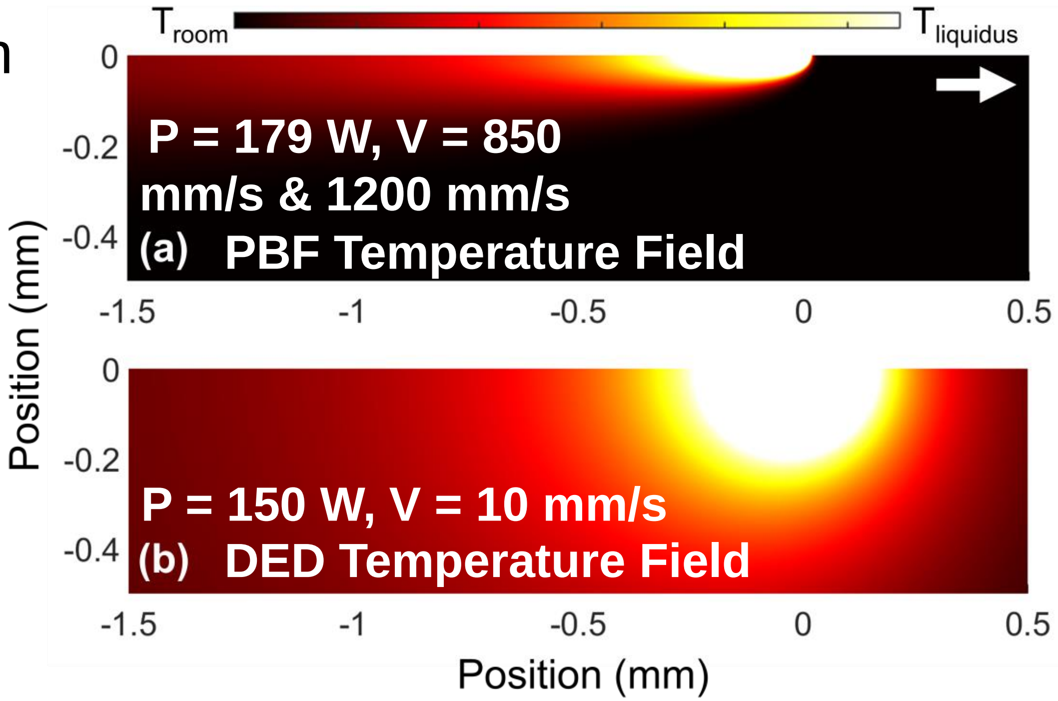
<u>Columnar-To-Equiaxed Transition (CET) Predictions</u>
- How does PBF compare to the DED process?
- What amount of nucleation is required?

<u>Ultrasonic Cavitation Experiments</u>
- Does the technique work for PBF?
- What are the ultrasonic tip conditions?

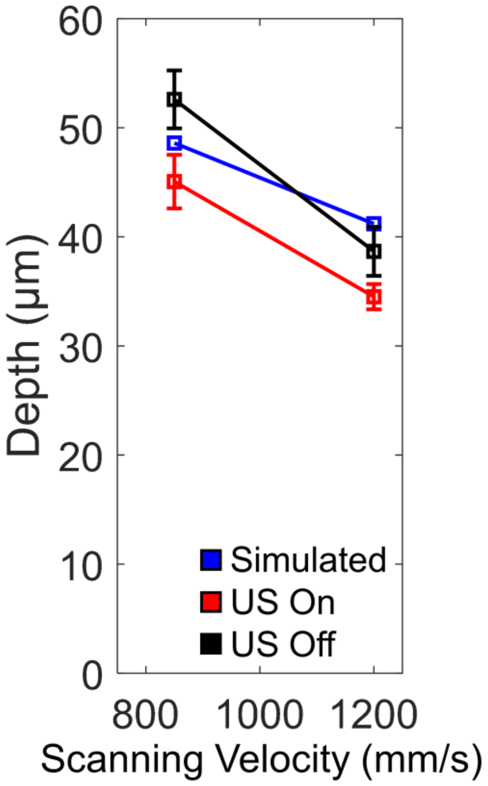
Thermal Simulations of the DED & PBF Processes

- Rosenthal Equation point source model
  - Used effective thermophysical values to account for variation with temperature
- Simulated with experimental PBF and reported DED processing parameters
- Extracted temperature gradient and solidification rate

$$T(x,z) = T_0 + \frac{\eta P}{2\pi R k_{eff}} \exp\left(-\frac{v(x+R)}{2\alpha_{eff}}\right)$$



Experimental vs. Simulated PBF melt depths



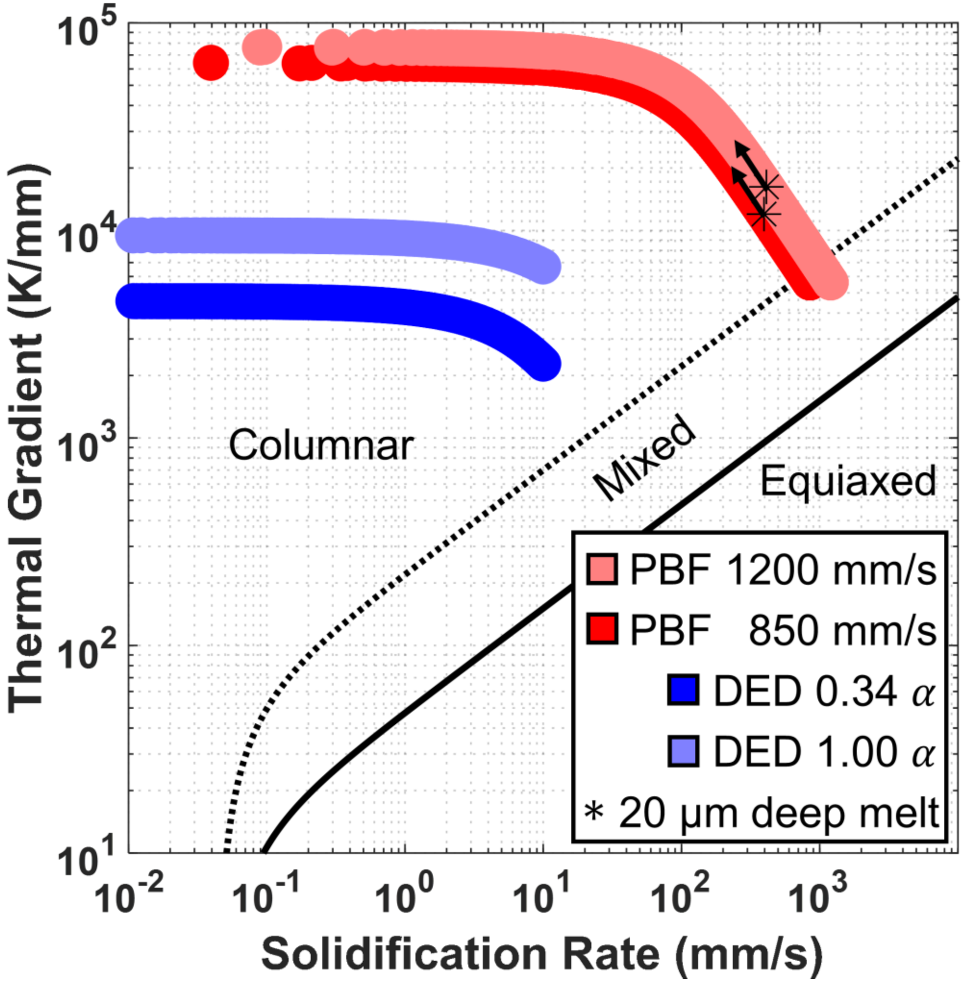
Prediction of Morphology & CET Curves

- Estimated columnar vs. equiaxed using experimentally-calibrated Hunt's criterion curves [5]
  - 0.34 & 1.00 α for DED due to uncertainty

$$Equiaxed: G < 0.617\, N_0^{1/3}\left(1 - \frac{\Delta T_N^3}{\Delta T_c^3}\right)\Delta T_c \qquad \Delta T_c = \left(\frac{v_d C_0}{A}\right)^{1/2}$$

$$Columnar: G > 0.617\, (100 N_0)^{1/3}\left(1 - \frac{\Delta T_N^3}{\Delta T_c^3}\right)\Delta T_c$$

- PBF has higher thermal gradients and solidification rates
- Upon layering, PBF microstructure returns to the columnar region



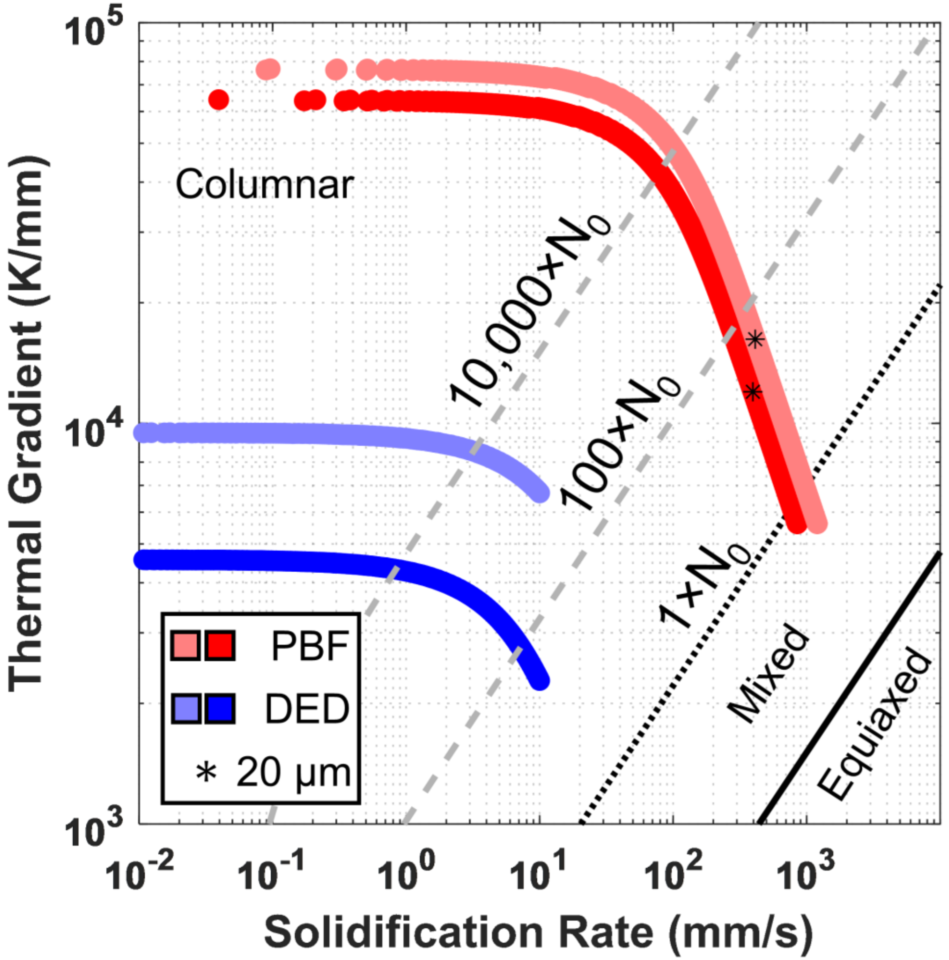
[5] S.L. Kuntz, "Feasibility of attaining fully equiaxed microstructure through process variable control for additive manufacturing of Ti-6Al-4V." (2016), M.S. Thesis, Wright State University

Increasing Nucleant Particles

- ❖ Ultrasonic-induced grain refinement mechanism: fracture of dendrite tips
- ❖ Leads to increase in heterogenous nucleant particles

$$Columnar:\ G > 0.617\ (100\ \boldsymbol{N_0})^{1/3}\left(1 - \frac{\Delta T_N^3}{\Delta T_c^3}\right)\Delta T_c$$

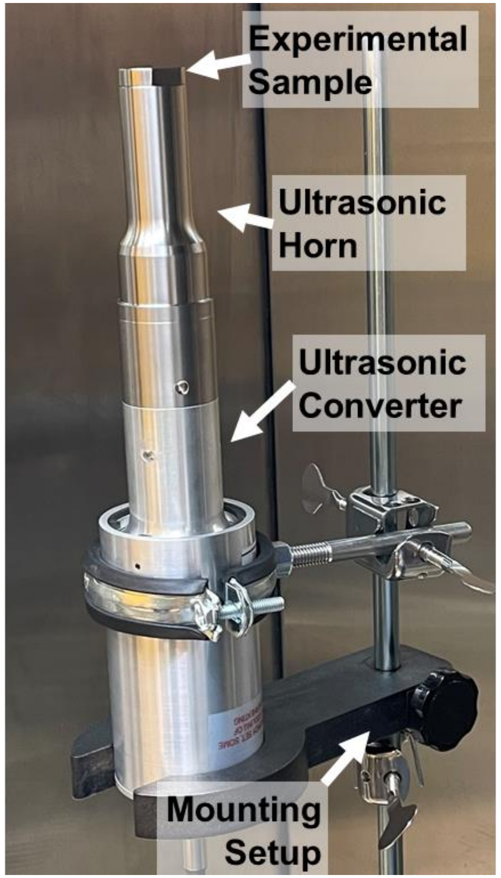
- ❖ Need to increase nucleant particles by a factor of 10^2 -10^4 times
- ❖ If suitable for DED, should also be compatible with PBF

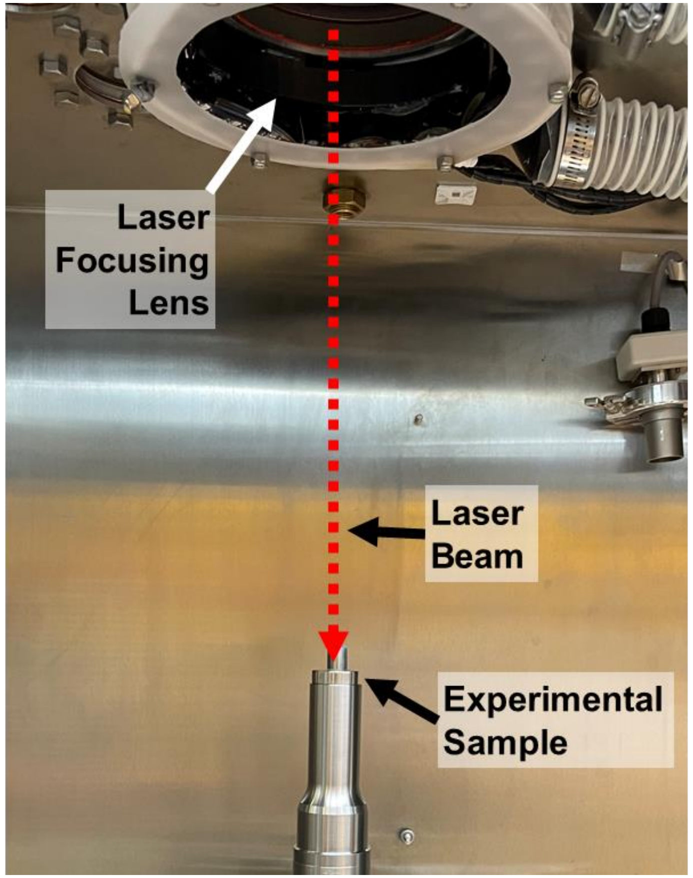


Experimental Setup

- Configurable Architecture Additive Testbed (CAAT) at NASA LaRC
- 1070 nm TEM00 laser (179 W effective power used for processing)
- 500, 850, 1200 mm/s scanning velocities

Experimental Setup





Measurement of Ultrasonic Tip Displacement

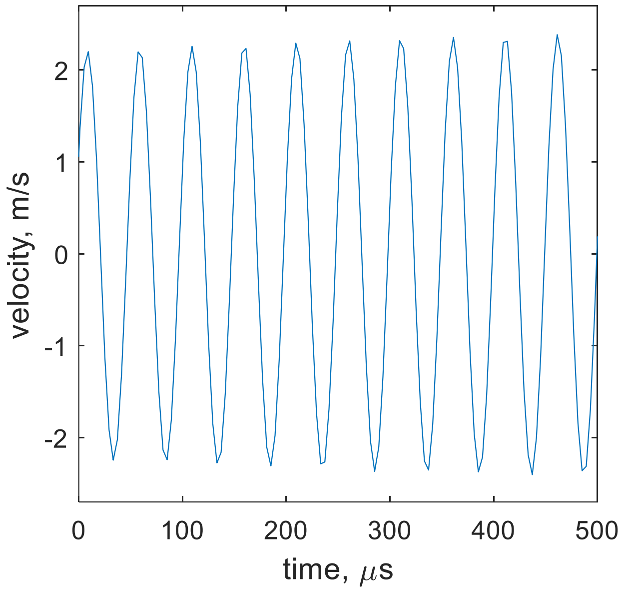
- Velocity measured via Doppler vibrometer (LDV)
  - Velocity → displacement → acoustic intensity

- 12.7 mm diameter Ti-6Al-4V sonicator probe at 12.4 µm sinusoidal displacement amplitude

- Ultrasonic intensity $I = 3350\ W/cm^2$, >30 times higher than $100\ W/cm^2$ approximate cavitation threshold [4] for light metal alloys

$$I = \frac{1}{2}\rho c(2\pi f A)^2$$

Sonicator probe velocity measurement via LDV



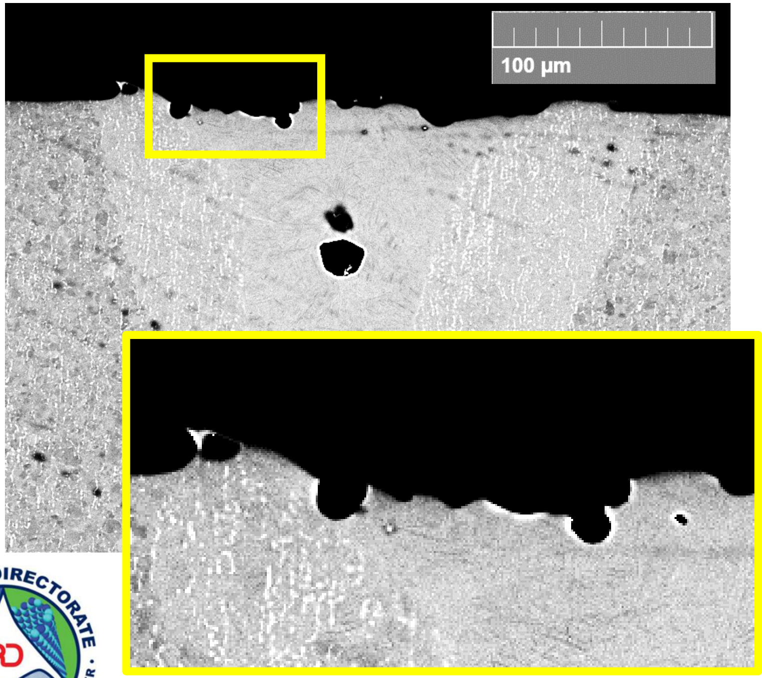
12.7 mm probe velocity measured via LDV

[4] Todaro, C. J., et al. "Grain structure control during metal 3D printing by high-intensity ultrasound." *Nature communications* 11.1 (2020): 1-9.

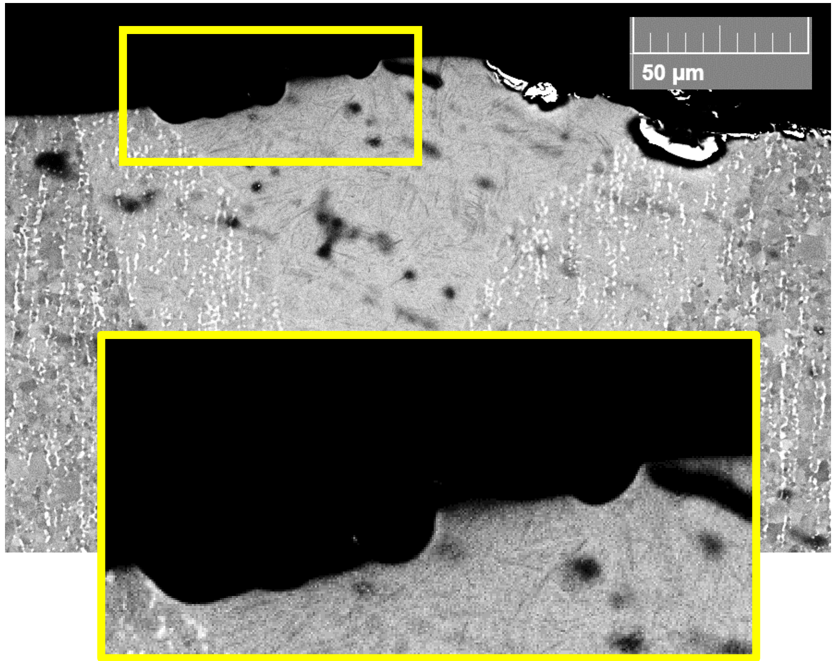
Evidence of Cavitation

- Evidence of cavitation in 500 mm/s & 850 mm/s
- Time-scales with bubble formation & collapse ~100 µs
- Slow velocity = longer melt pool = more time for cavitation

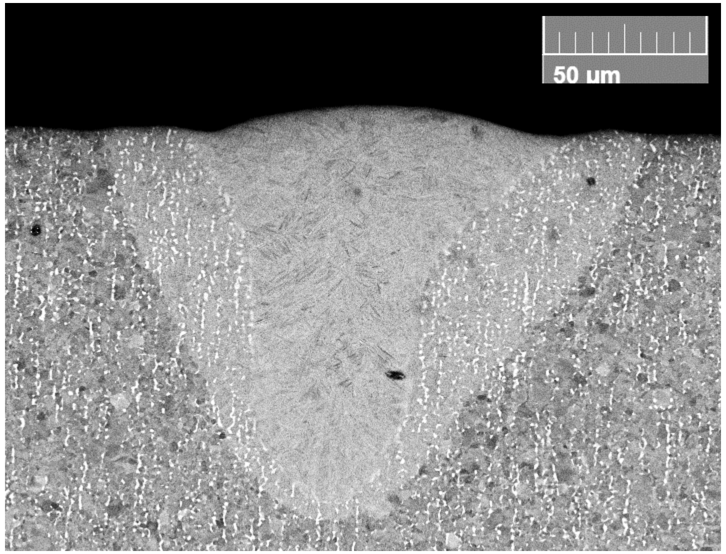
500 mm/s



850 mm/s

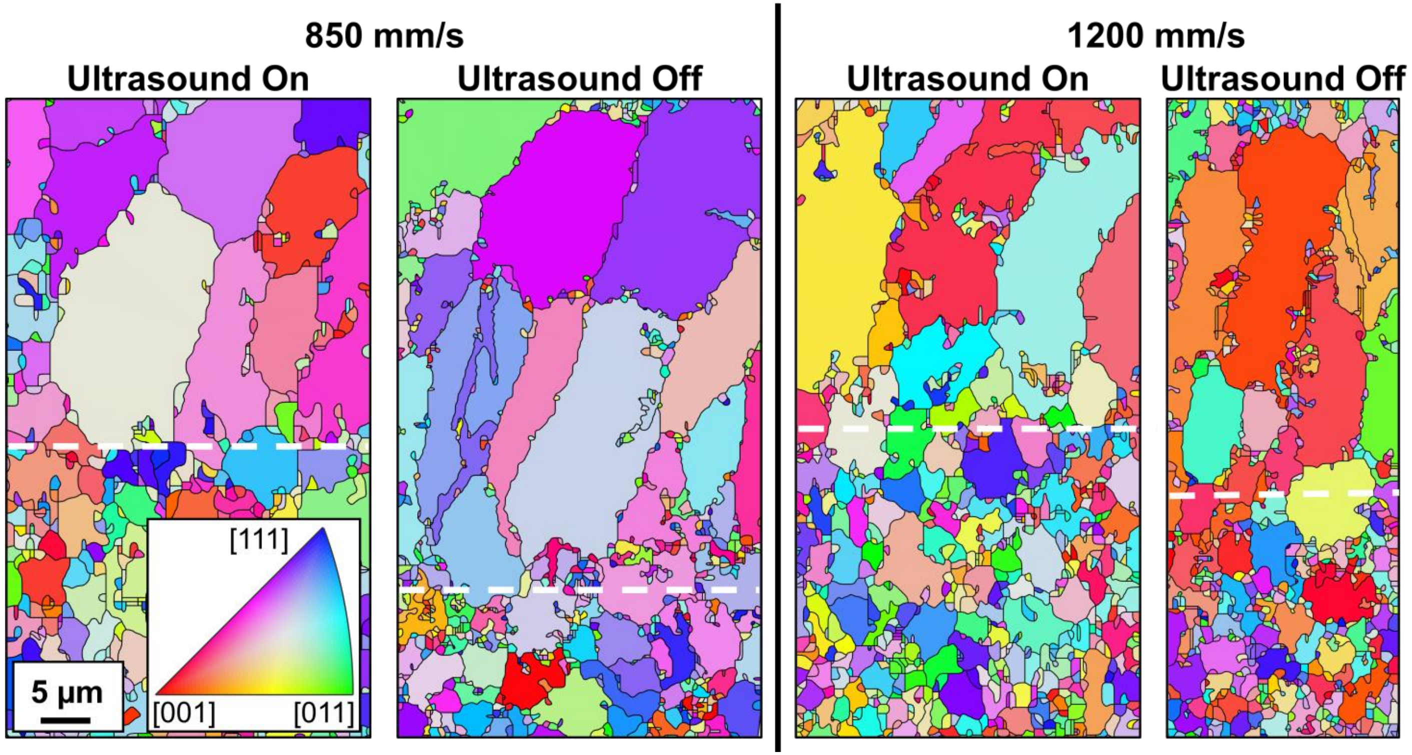


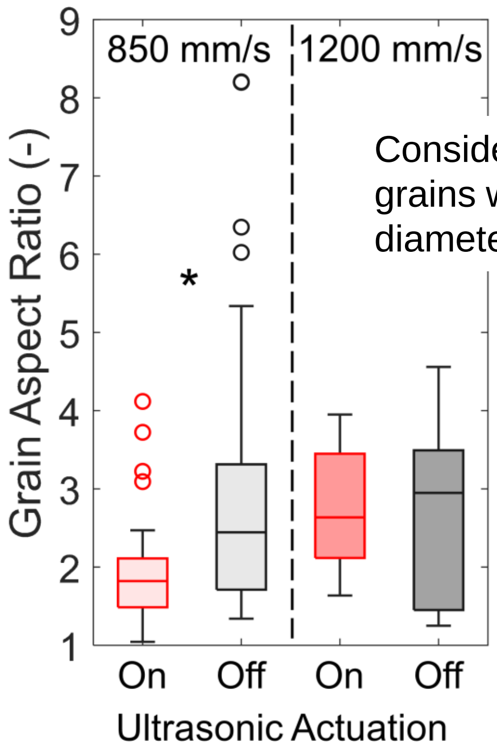
1200 mm/s



Effect on Microstructure

- Evidence suggests that 850 mm/s velocity modifies reconstructed grain aspect ratio
  - No effect observed at 1200 mm/s velocity
- Increased residence time seems to promote more cavitation





Conclusions

- ❖ Ultrasonic cavitation-induced grain refinement appears to be compatible with PBF solidification conditions
- ❖ Evidence indicates that cavitation occurred between 500 mm/s and 850 mm/s
- ❖ Modification to reconstructed grain aspect ratio was observed under 850 mm/s velocity conditions

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