High speed imaging of metal additive manufacturing processes

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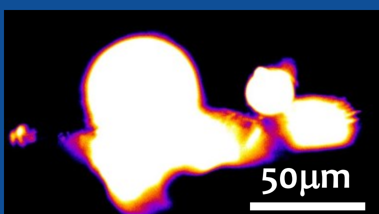

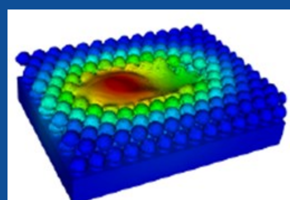

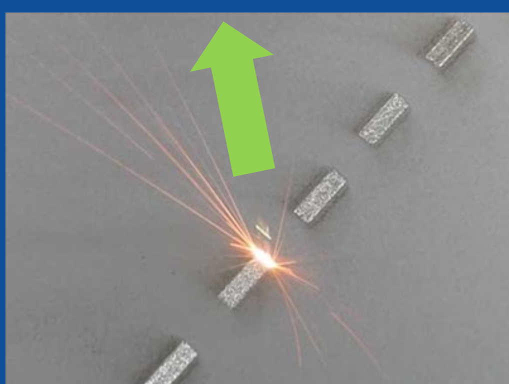

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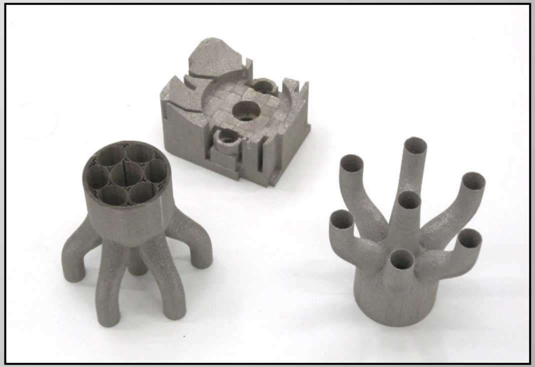
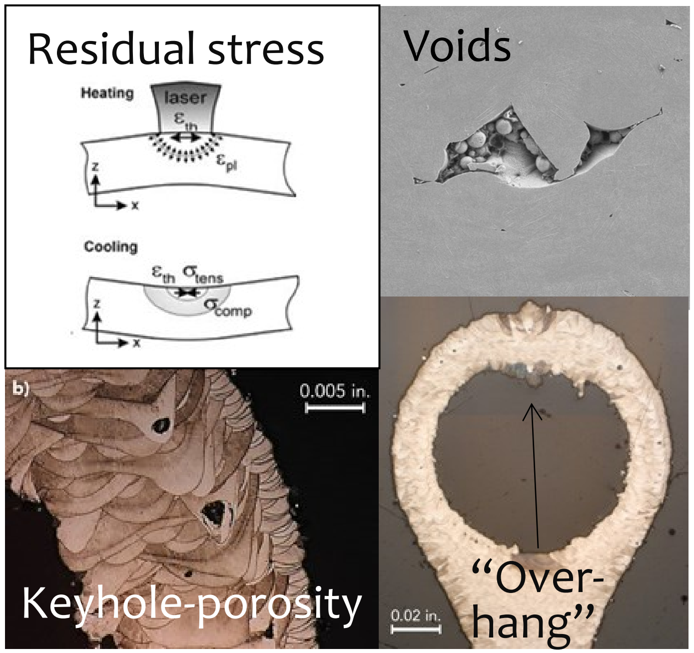
Metal additive manufacturing based on Selective Laser Melting of powders has greatly enabled design flexibility



LLNL efforts in this area aimed at modeling and qualification of SLM, process monitoring, and **improved model validation**

Despite apparent simplicity of technique, multiple physical phenomena govern SLM

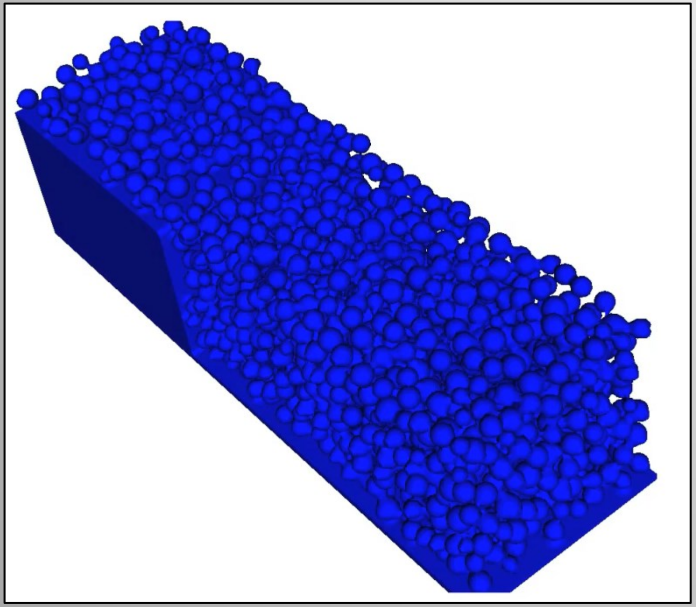


Absorption
Vaporization
Capillarity
Hydrodynamics
Marangoni Convection
Wetting/dewetting
Phase transformation
Phase separation
Convection
Radiation
…

Experimentally probing the laser melting process *in situ* can yield insight to these multiple physical effects

Model-driven experimentation is sought to minimize defects which can limit AM performance

Laser powder melt simulation

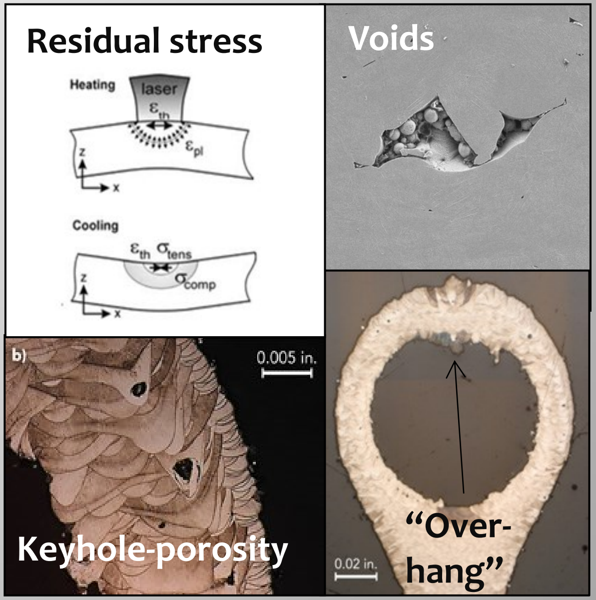


S. Khairallah and A. Anderson

Physics

Absorption
Vaporization
Capillarity
Hydrodynamics
Marangoni
Convection
Wetting/dewetting
Phase transformation
Phase separation
Convection
Radiation
…

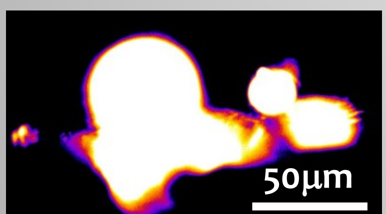
Defects

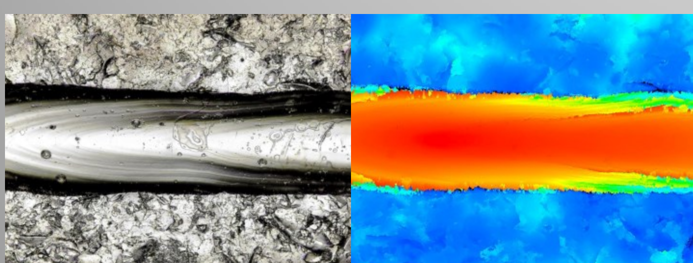


Goals

- Demonstrate high speed, microscopic technique to directly probe heating, melting and wetting of metal powders used in SLM
  - Extend to higher effective scan rates, higher powers & higher frame rates
- Compare to simulations to improve understanding of SLM process, validate models

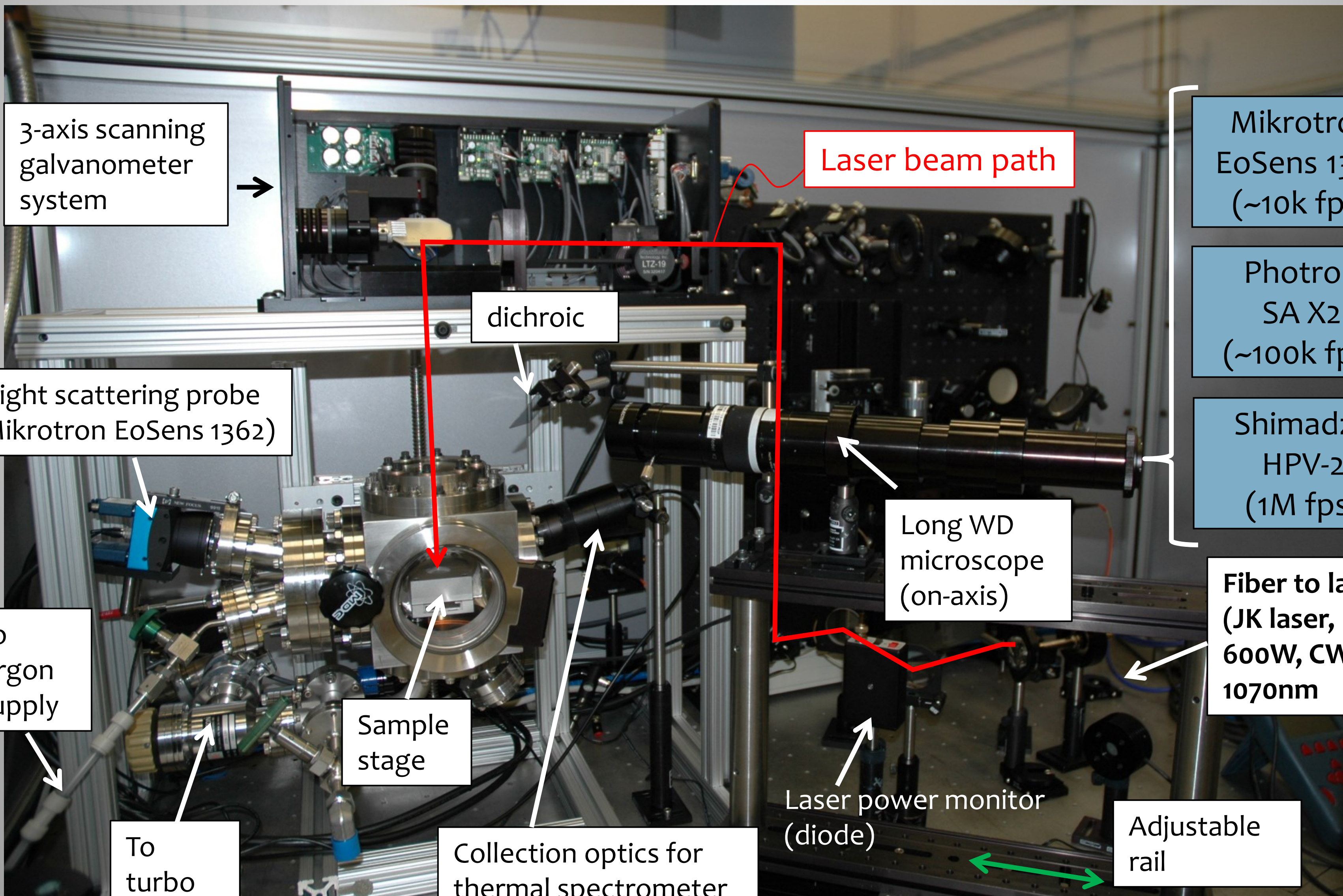
Approach





- Use high frame-rate CMOS camera microscopy to image single layer, metal particle bed melting under varying laser and environmental conditions
- Use self-illumination incandescence from heated particle to characterize melt pool dimensions, particle/splash ejection
- Compare thermal emission history with final material deposition morphologies

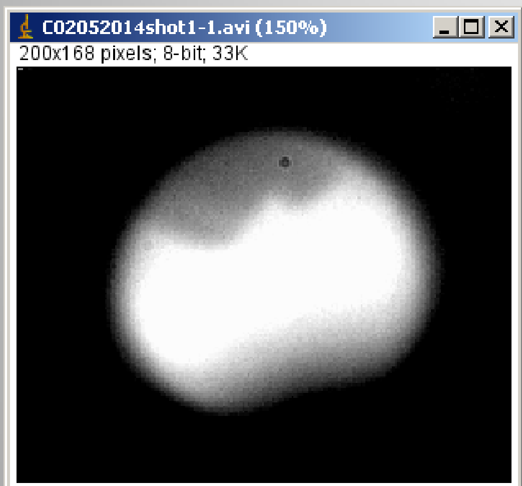
Experimental setup

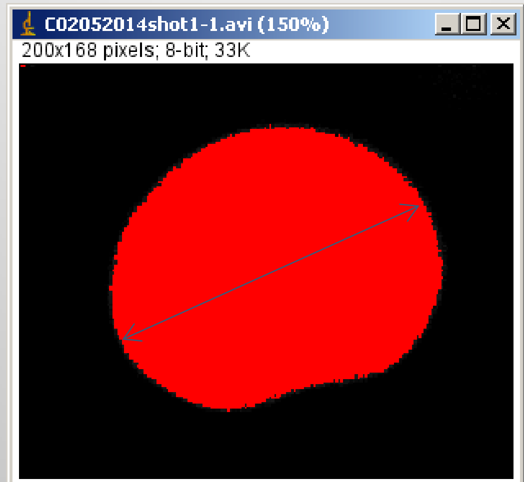


Analysis of single particle shape evolution from high speed image files

Raw 8-bit image
(10kHz, 200x168pix)

Threshold mask (25-255)

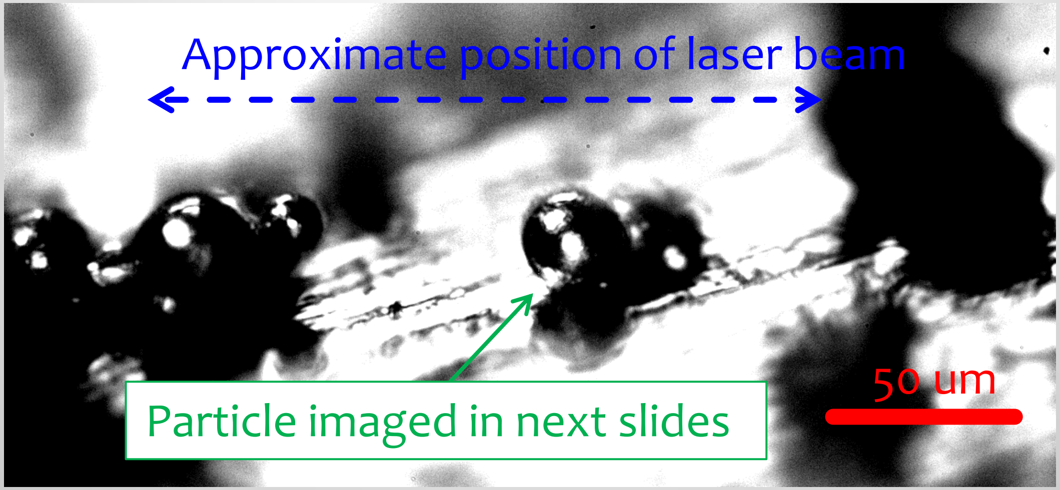




Feret's diameter
Area
Circularity
Center of mass
Intensity
…

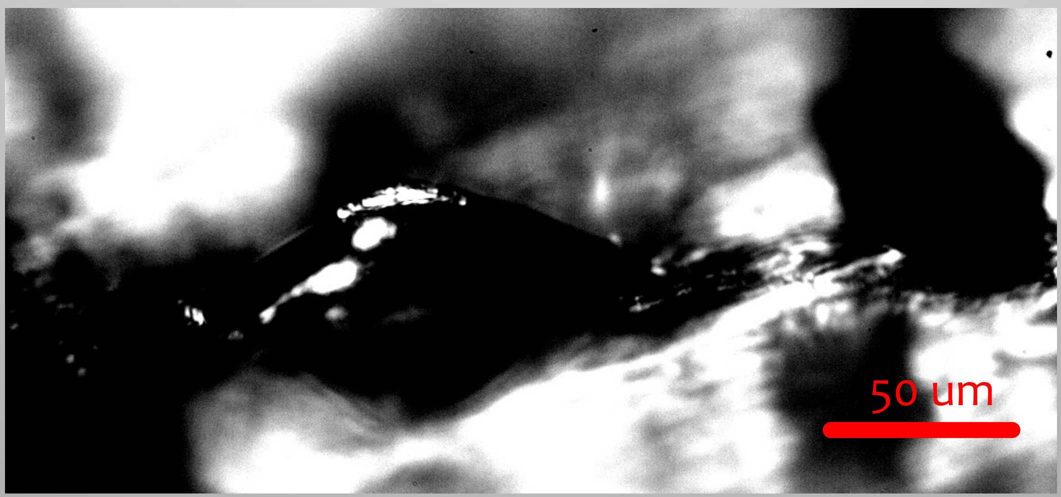
Initial and final morphology of laser-induced melting of sparse 316L layer

Pre-shot



5~50 W of 10.6 μm light into 200 μm ($1/e^2$), τ=50 ms

Post-shot



10 kHz imaging of laser-generated incandescence (total movie time 70 ms)

Thermo-isolated heating time:

$$\alpha\pi R I\tau = 4/3\pi R^3\rho C T_m$$

$\tau_{Hc} \sim 4/3R\rho CT_m/\alpha I \sim$ 0.75 ms

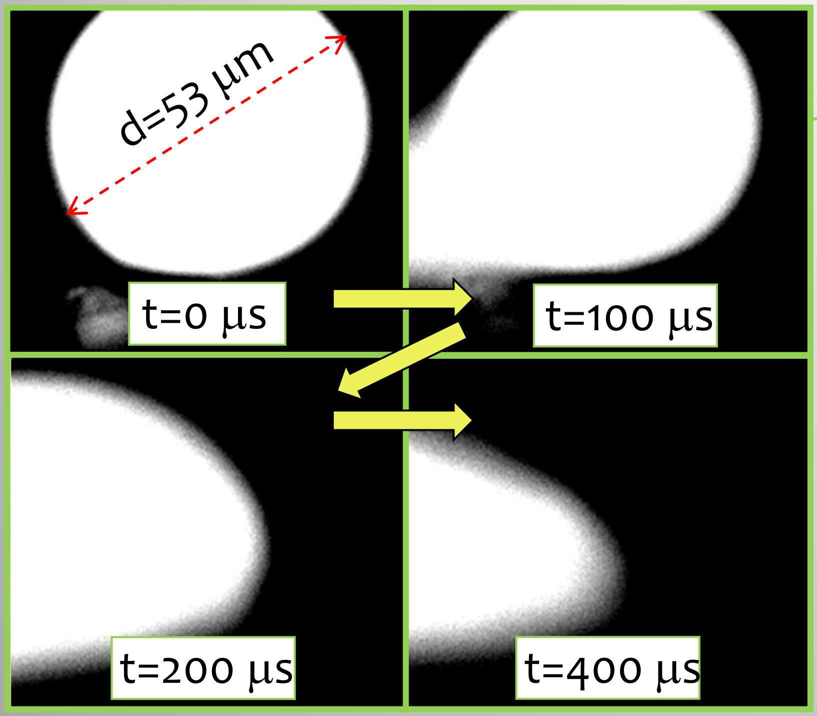
Thermal conduction time:

$\tau_c \sim R^2/D$, D-0.04 cm^2/sec

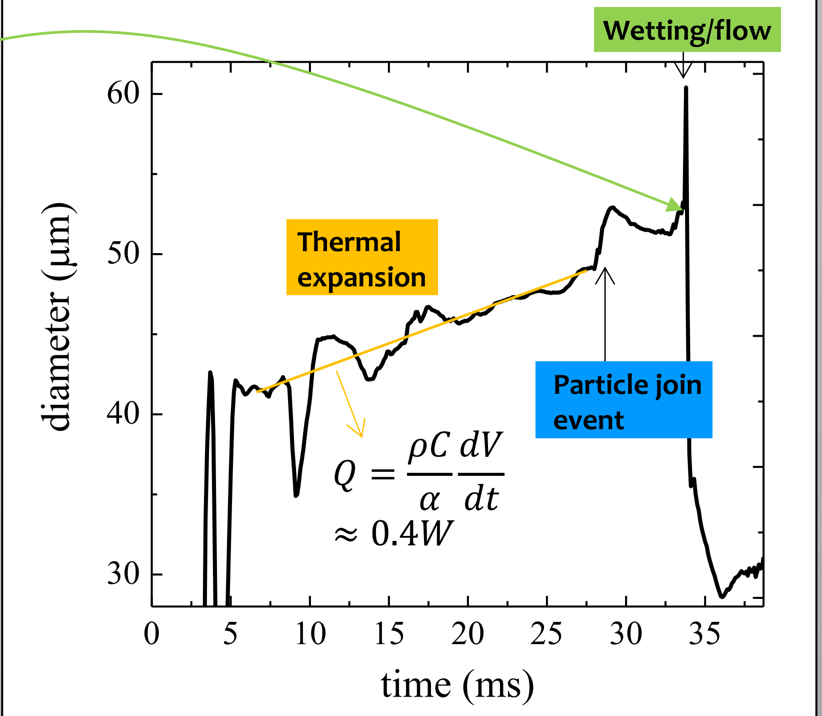
for R=15 µm steel particles:

τ_c=56 µs

Dynamics of steel 316L particle was irradiated with IR laser light was revealed using 10k fps imaging



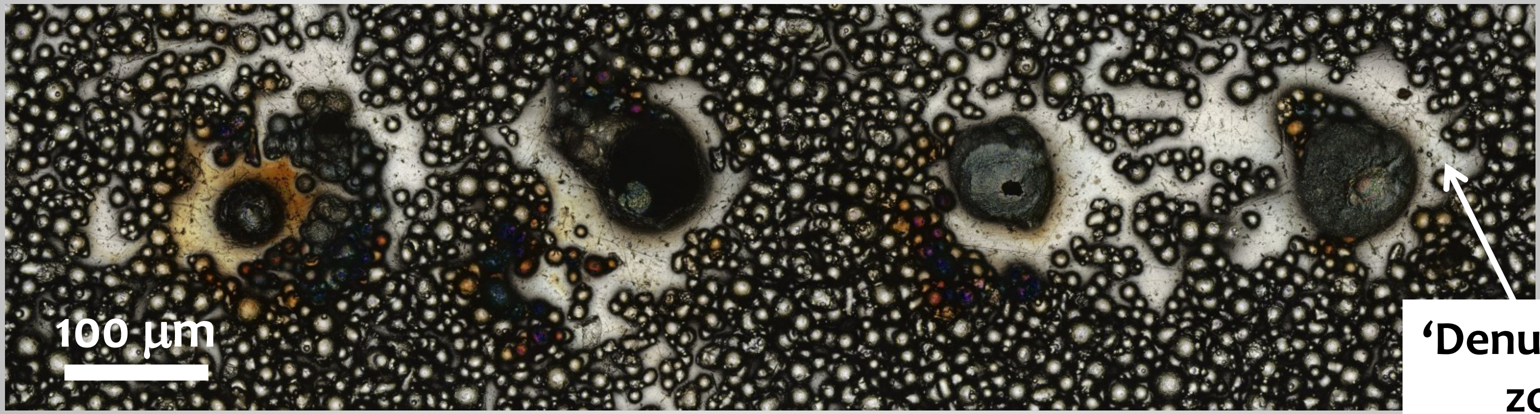
Measured particle dynamics captures expansion, melting & wetting



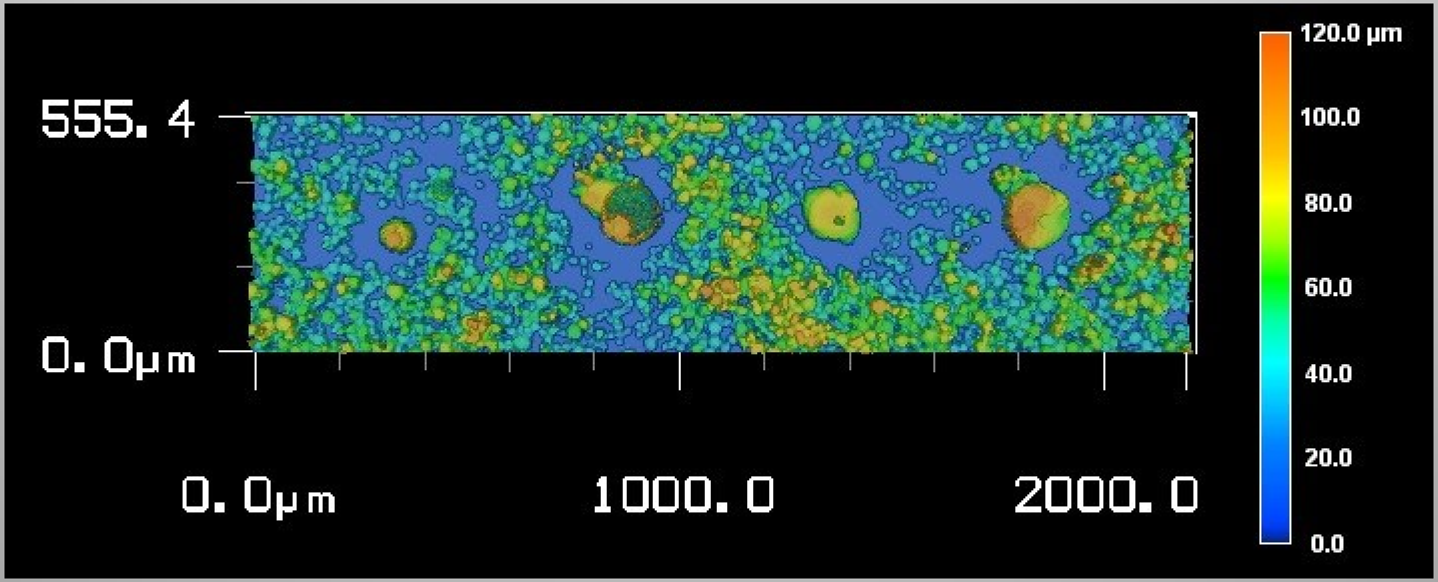
~4 ms delay observed between melting and wetting indicates highly non-uniform heat distribution

Single layer of SS 316L powder exposed to single ~10W pulses shows conglomeration and denudation effects

Laser spot size: ~80 μm

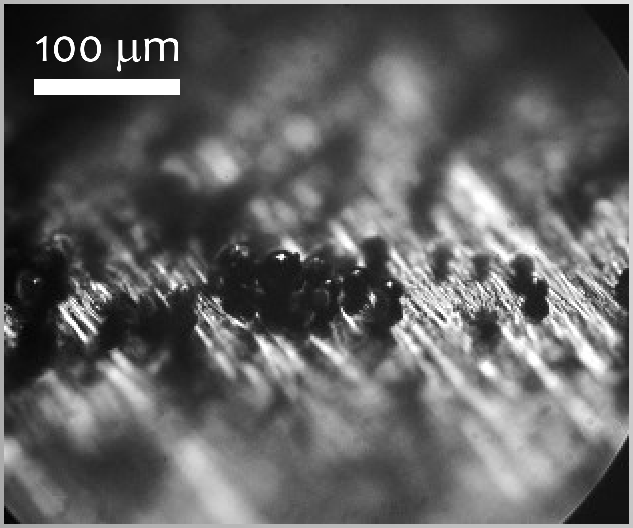


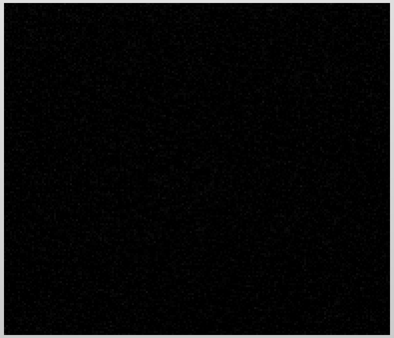
'Denudation' zone



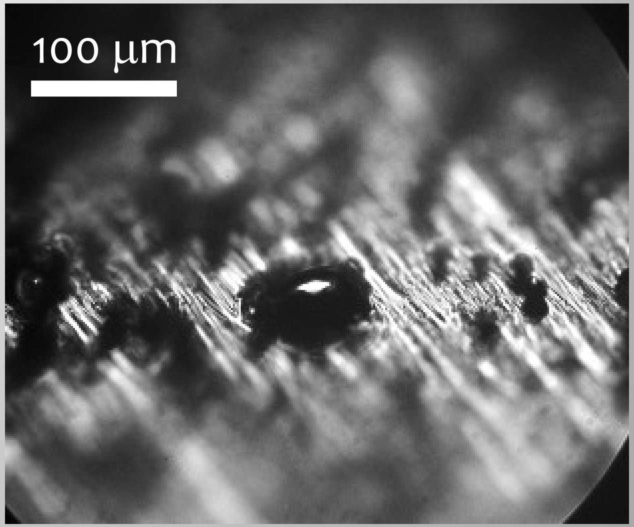
Steel 316L particle cluster irradiated with 100W, 50um $1/e^2$ Gaussian diameter beam: 1Mfps, 15us start delay, 100 frames total

before





after



- Apparent lack of wetting
- Fluid wave speeds ~10-17 m/s
- Droplet ejection at 12.6 m/s

Off-axis imaging of molten particle ejection with scanning beam (P=150W, a=50um, u=500 mm/s)

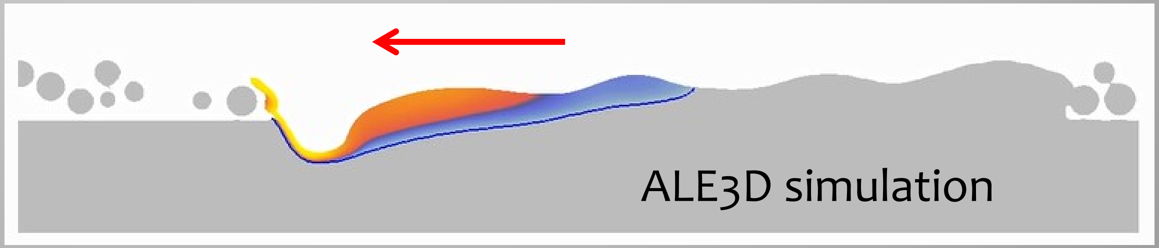
19 mm

3,775 frames/second

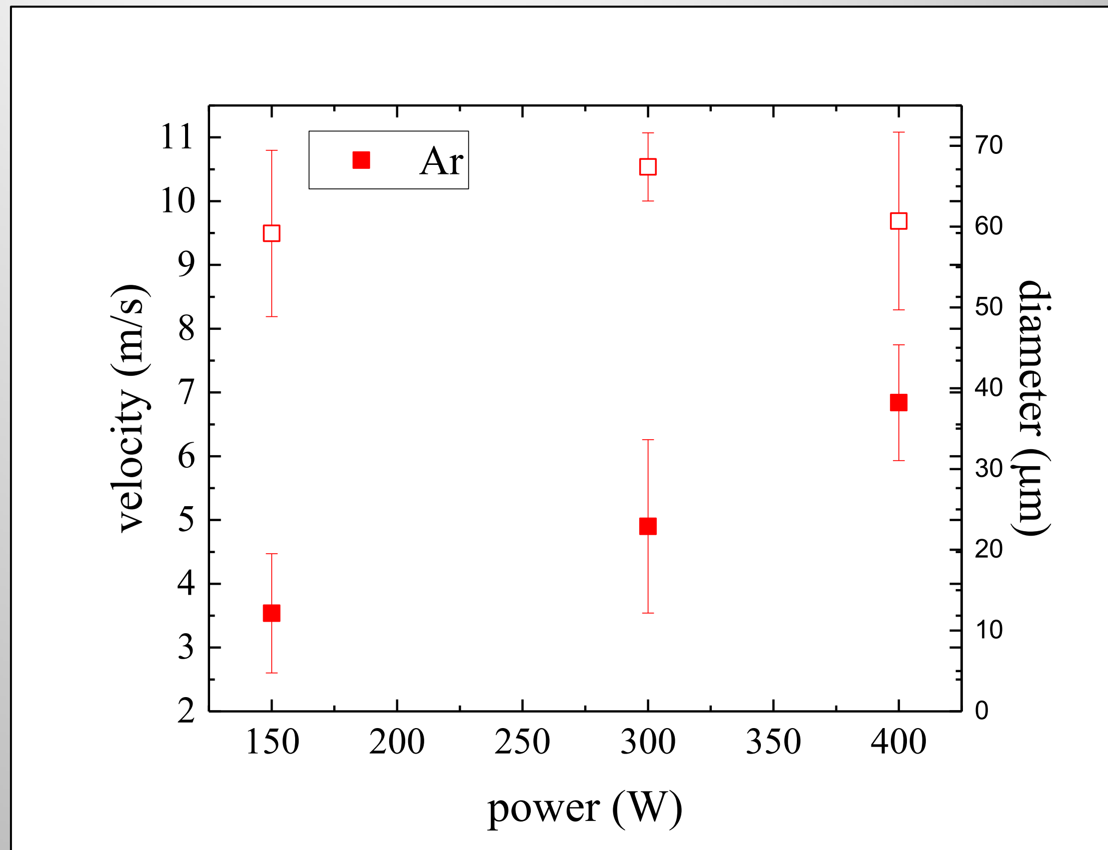
425 µm

250k frames/second

Evaporation-driven recoil momentum shapes melt track, ejects material



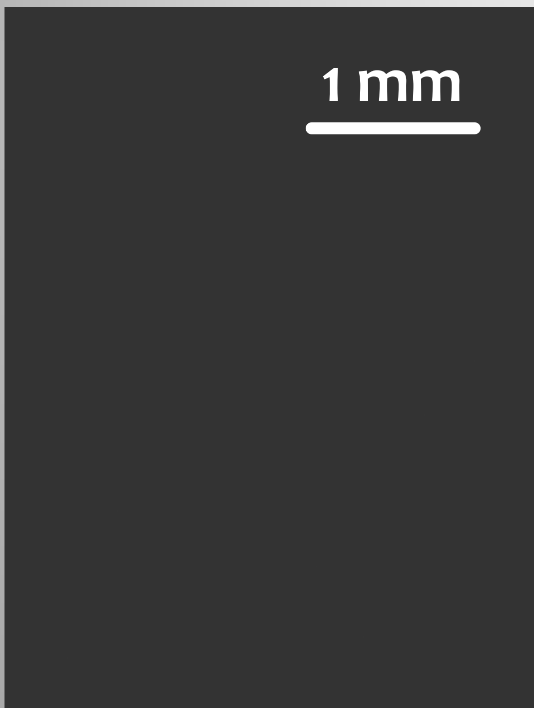
Measured ejection velocities and particle sizes as a function of laser power (1200 mm/s scan speed)

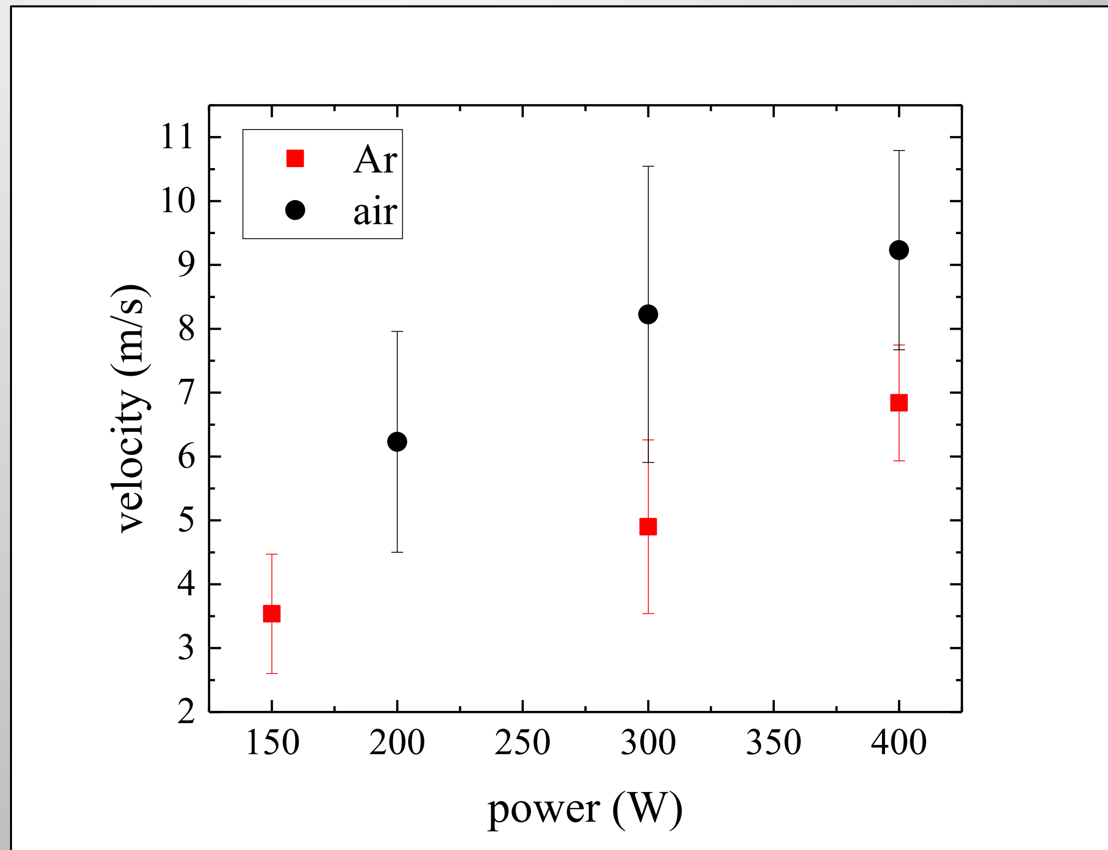


- Velocity increases with laser power due to increased recoil pressure
- Droplet size did not vary appreciably with laser power

Measured ejection velocities as a function of laser power (1200 mm/s scan speed): effect of oxidation

150W, 1200 mm/s





- Oxidation leads to increased heating, pressure
- Droplet size not affected by oxidation (~70µm, not shown)

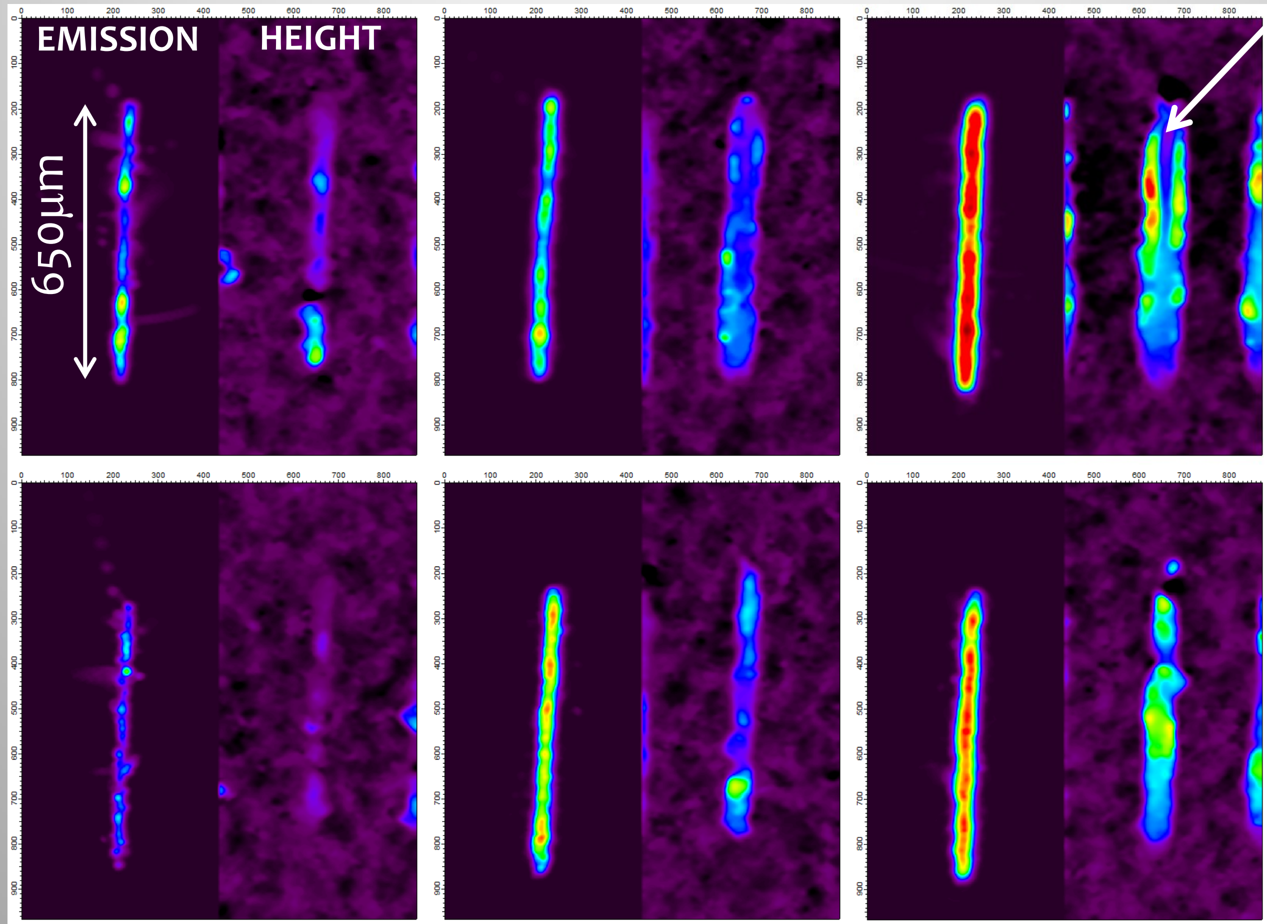
Comparison of thermal emission history and final deposited material morphology

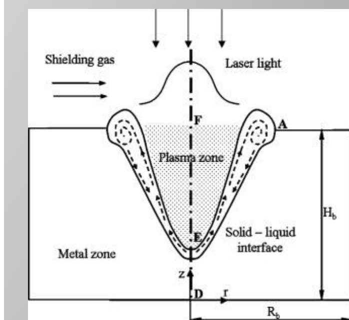
50W | 100W | 150W

"keyholing"

500 mm/s

1200 mm/s



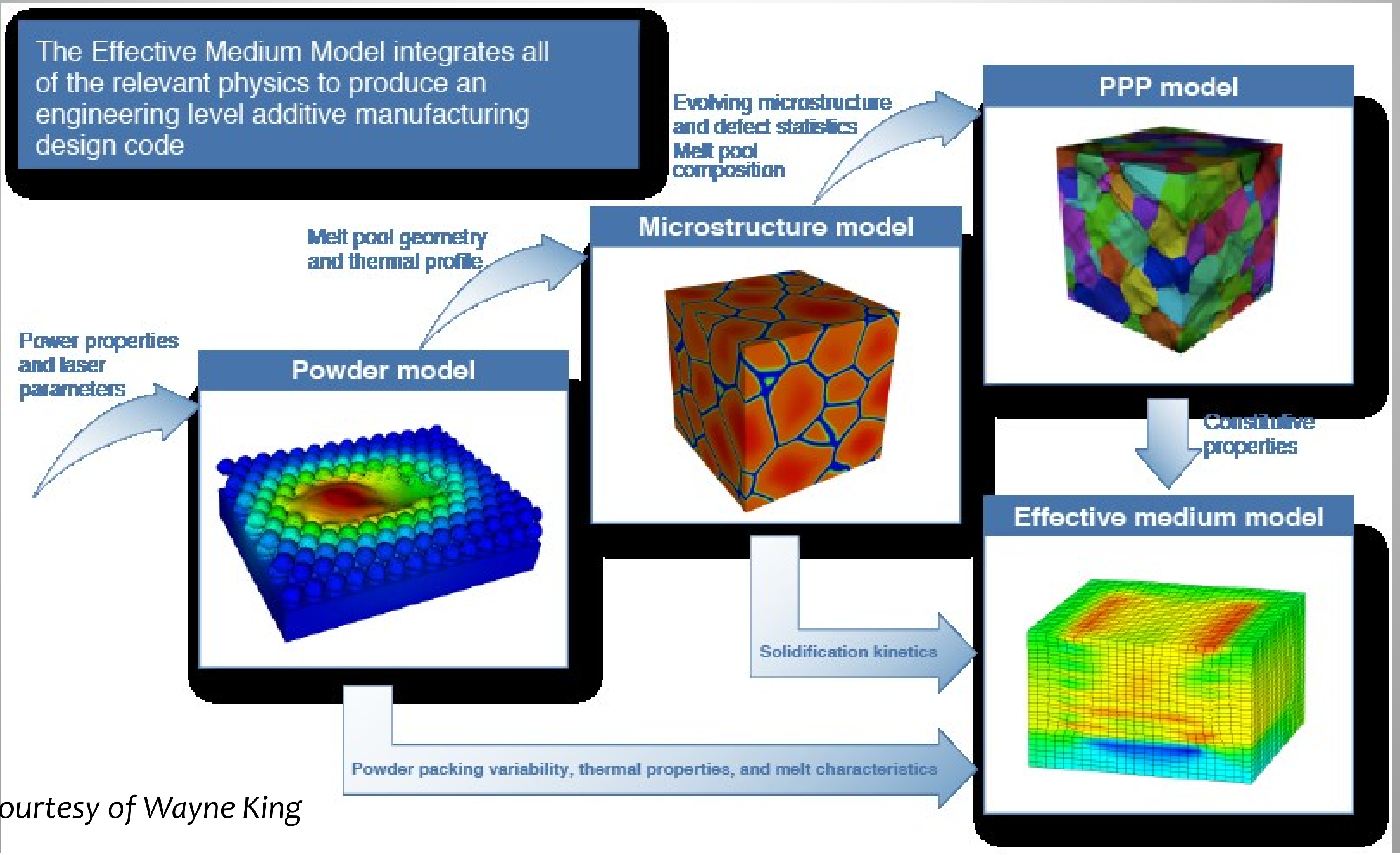


Summary

- An imaging test bench to monitor dynamic of laser-induced melting of stainless steel powders using high frame rate (up to 1 MHz) imaging was demonstrated
- Keyholing from evaporation-driven recoil pressure was observed at high laser power, with a threshold in agreement with reported predictions
- Delayed/frustrated wetting was observed, which could lead to large fluctuations and instability in droplet diameters
- Ejection velocities for typical SLM deposition conditions were on the order of 3-7 m/s, increasing with laser power and oxygen content
- Future work will include pulsed laser illumination and full 3D build temperature monitoring

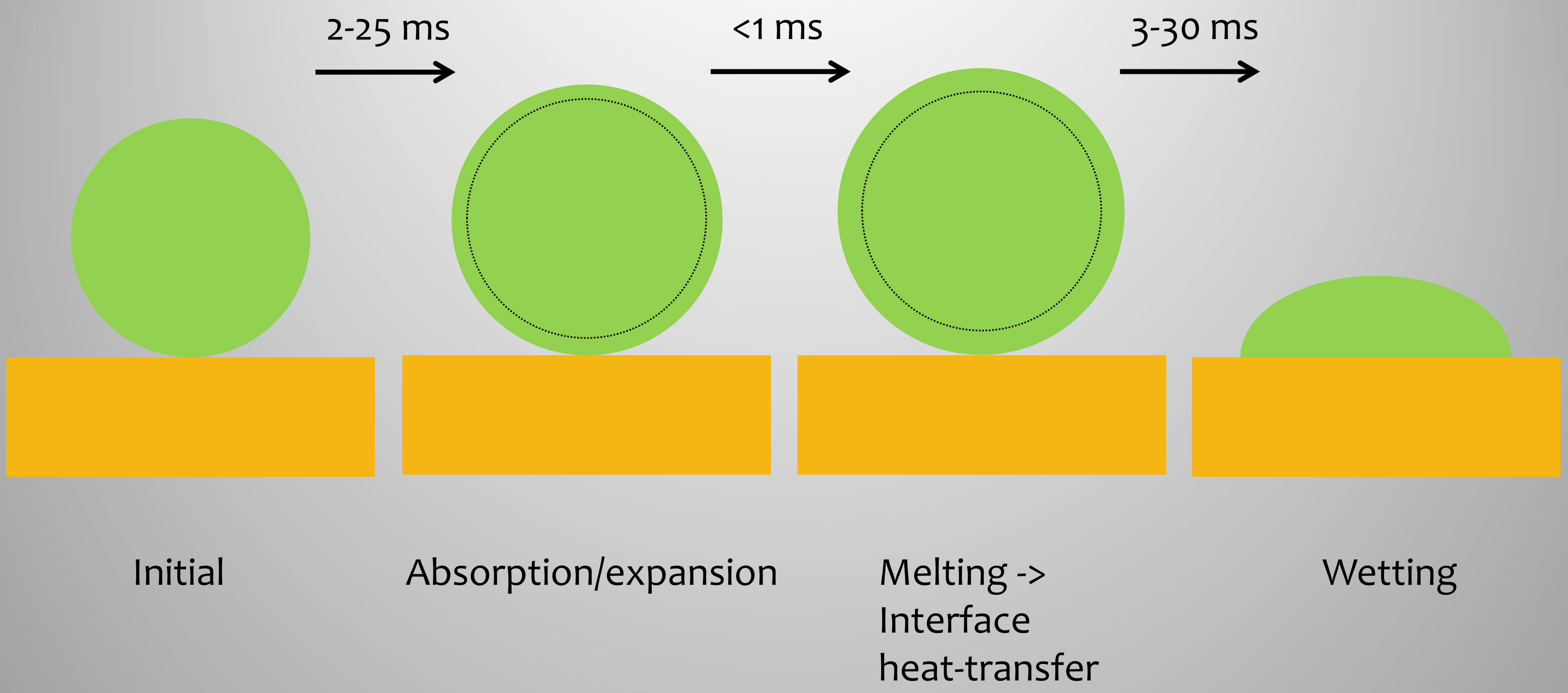
THANK YOU FOR YOUR ATTENTION!

High performance computing is being leveraged to *Accelerate Qualification* of Additive Manufactured parts



Courtesy of Wayne King

Analysis of melt-wetting dynamics



Estimating melt times and particle-substrate heat transfer under laser irradiation

Absorptivity for polished stainless steel at λ=10.6 µm is ~0.1

For the underlying substrate, with thermal conductivity the value near the melting point is k=36 W/m.K $\rightarrow$ T~112 C (won't melt substrate!)

Thermal conduction time: $\tau_c \sim R^2/D$, D-0.04 cm^2/sec for SS, R=15 µm

$\underline{\tau_c = 56\ \mu s}$

Thermo-isolated heating time: $\alpha \pi R I \tau = 4/3 \pi R^3 \rho C T_m$

$\tau_{Hc} \sim 4/3 R \rho C T_m / \alpha I \sim \underline{0.75\ ms}$

However, finite element simulations of a particle in thermal contact with the substrate, $\underline{\tau_{Hc} < 20\ ms}$

<u>Wetting time: Laplace pressure + Bernoulli Eq. $\rightarrow$ 1-10 µs</u>