Quantifying equiaxed versus epitaxial solidification in laser melting of CMSX-4 single crystal superalloy

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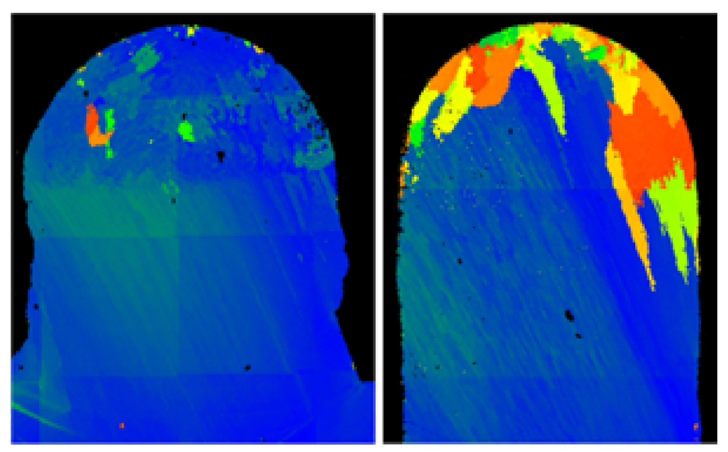
Motivation

Mixture of Columnar and Equiaxed Grains



Mokadem et al., Solidification and Microstructure, (2004)

- New grains with orientation different from the base material were often found in welding repaired nickel-based single-crystal superalloys
- Adjusting printing parameters are proven to be effective in mitigating stray grains formation
- Extend the parameters to LPBF conditions

Methods

Analytical solidification modeling based on constitutional undercooling

Temperature

$$T = T_0 + \frac{\eta P}{2\pi k\sqrt{x^2+y^2+z^2}} \exp\left[\frac{-V(\sqrt{x^2+y^2+z^2}-x)}{2\alpha}\right]$$

Thermal gradient

$$G = |\nabla T| = \left|\frac{\partial T}{\partial x}\hat{i} + \frac{\partial T}{\partial y}\hat{j} + \frac{\partial T}{\partial z}\hat{k}\right| = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2}$$

Solidification Isotherm Velocity

$$v_T = V\cos\theta = V\frac{\frac{\partial T}{\partial x}}{\sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2}}$$

Local Stray Grain Area Fraction

$$\Phi = 1 - e^S$$

$$\text{where } S = \frac{-4\pi N_0}{3}\left(\frac{1}{(n+1)(G^n/av_T)^{1/n}}\right)^3 = -2.356\times 10^{19}\left(\frac{v_T}{G^{3.4}}\right)^{\frac{3}{3.4}}$$

Computational fluid dynamics (CFD)

Recoil Pressure

$$\Pr \cong 0.54 P_0 \exp\left(\Delta H_{LV}\frac{T - T_{LV}}{RTT_{LV}}\right)$$

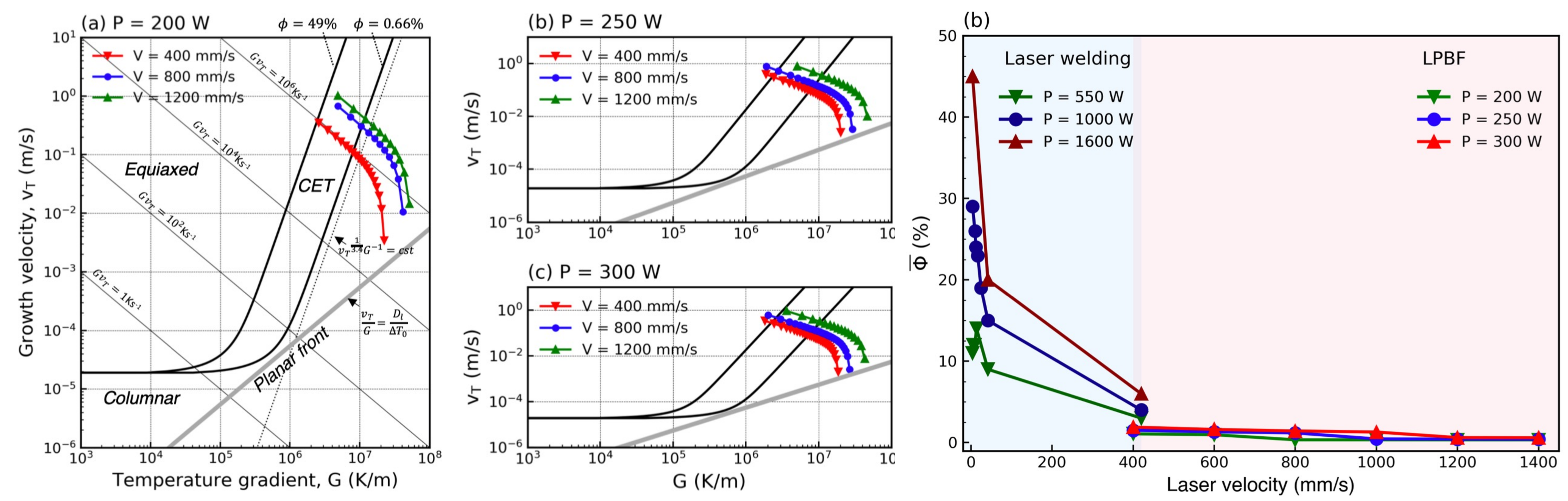
Surface tension coefficient including Marangoni flow

$$\sigma = 1.79 - 9.90\cdot 10^{-4}(T - 1654K)\ \mathrm{Nm}^{-1}$$

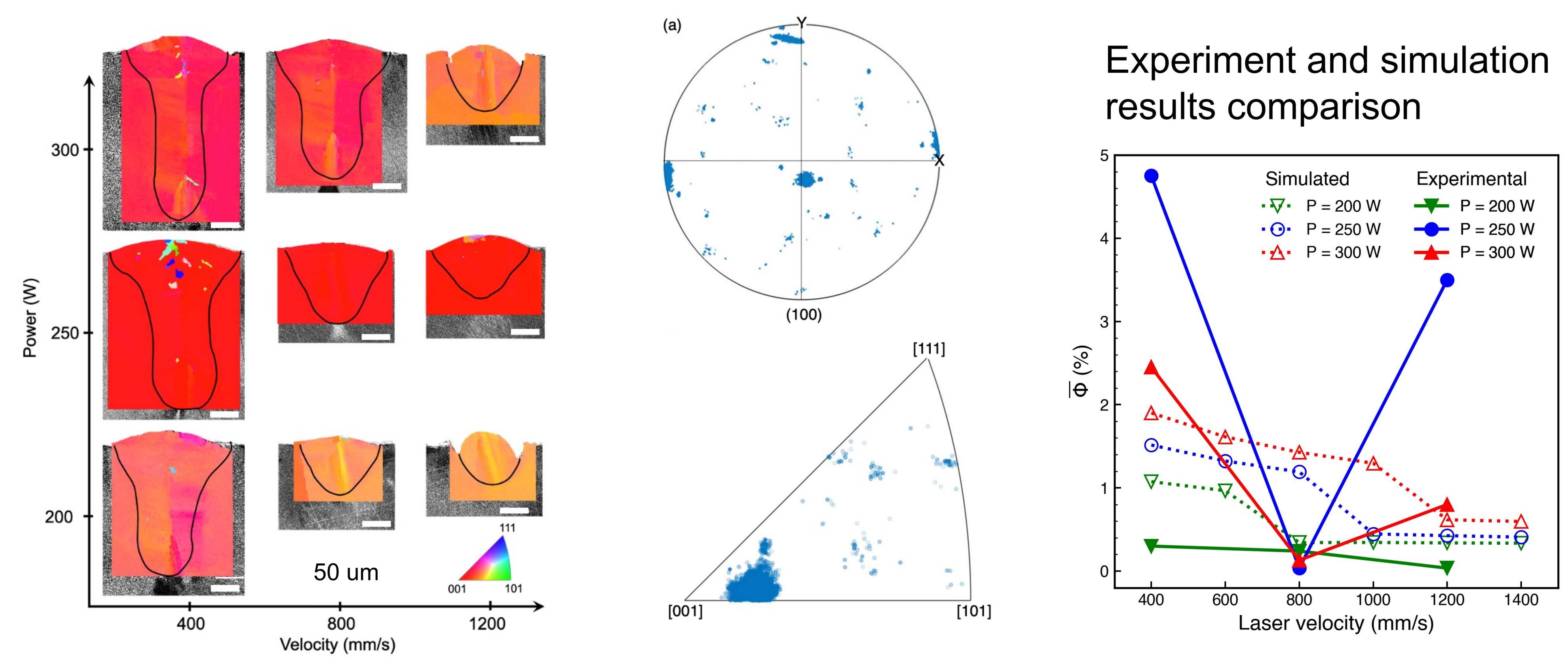
Vitek, The sixth internation EPRI conference, (2004)
Cho et al., *Journal of Physics D*, (2006)

Results

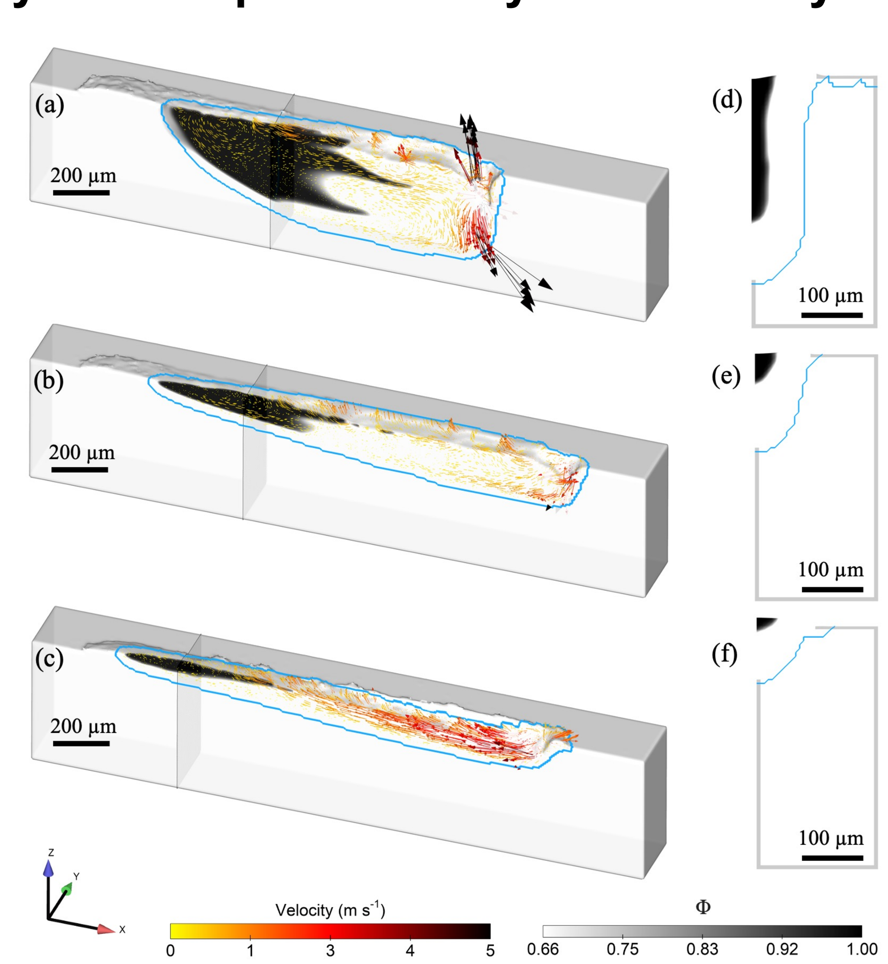
Microstructure selection map for CMSX-4 under laser powder bed fusion conditions



EBSD mapping for single bead laser melting of CMSX-4 single crystal

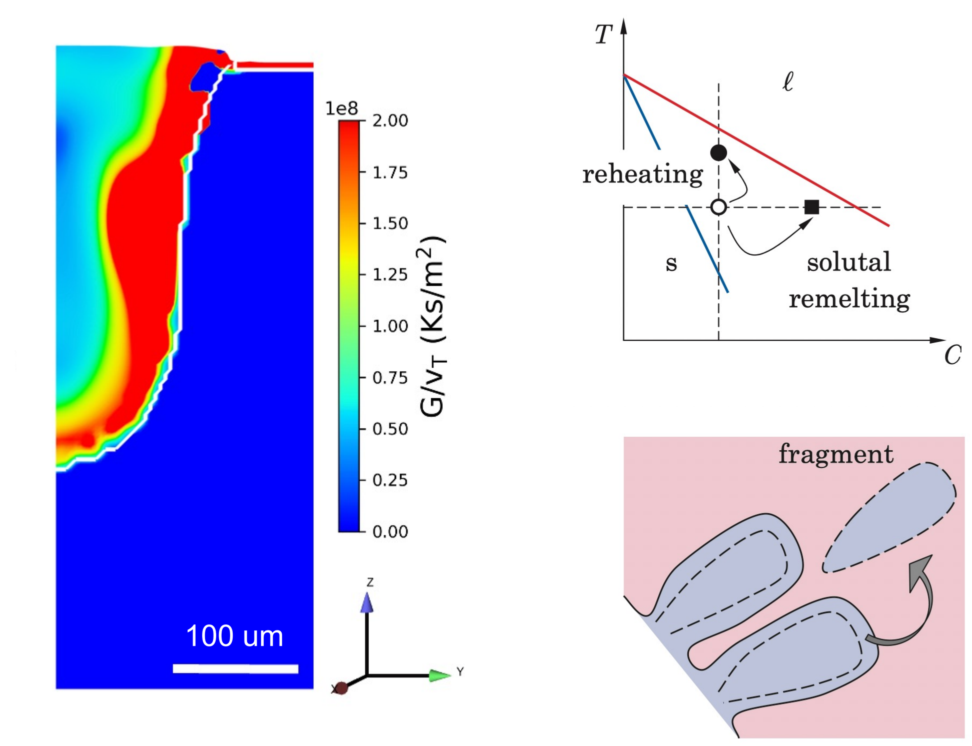


Fluid velocity fields represented by fluid velocity vectors and local stray grains propensity



- The discrepancy between EBSD results and analytical solidification result can not be explained by the constitutional undercooling theory
- dendrite fragmentation caused by vigorous fluid flow in the melt pool can also lead to the formation of new grains near the melt pool boundary
- Strong backward flow was observed in the V = 1200 mm/s case and a chaotic, fluctuating flow in the V = 400 mm/s was observed in CFD simulation

Conclusion



- Heterogeneous nucleation is the primary mechanism leading to the formation of new grains where features low G/v_T
- Stray grains near the melt pool boundaries are exclusively observed in deep keyhole shaped melt pools, which suggests that the effect of dendrite fragmentation caused by strong fluid flow may be potent enough to be considered
- Besides higher laser scanning velocity and lower power, a stable keyhole and minimal fluid velocity also mitigate stray grain formation and preserve epitaxial growth

J.A. Dantzig et al., Solidification, (2016)

Future Work

- Interaction between two or more laser tracks to evaluate the possibility of stray grain removal
- Effect of powder in maintaining single crystal structure and introducing of extra nucleation sites
- When layers of materials are to be deposited, scan strategy will also play an important role
- CFD modeling of more complex interactions mentioned above

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