ME – PhD Thesis Colloquium

Spatio-temporal solidification in metal additive manufacturing: A study in similitude

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ABSTRACT

Laser-based metal additive manufacturing (AM) is often hindered by unpredictable defects that form within opaque, microscopic melt pools in mere microseconds. Extreme thermal gradients and rapid solidification generate complex, non-equilibrium microstructures, making direct in situ observation and mechanistic understanding highly challenging. Consequently, current process qualification relies heavily on costly simulations and extensive trial-and-error. To address this, we present a dimensional analysis framework utilizing transparent organic analogues to study AM solidification dynamics. Our two-step similitude procedure first maps a 3D laser melt pool to a 2D thin-film configuration via a classical semi-analytical heat conduction solution, translating laser parameters (P_l, v_l) to a directional solidification setup (G_T, v_p). We then utilize the Succinonitrile (SCN) system to reliably mimic ferrous alloy behavior during laser processing.

To investigate solidification amid heterogeneities—relevant to the AM of metal matrix composites—we introduce rigid, insoluble particles into the solidification path using high-precision lithography. By employing varying geometries—a square with a flat face ($\kappa_p = 0$), a circle with constant curvature ($\kappa_p = 1/r$), and a triangle with a sharp vertex ($\kappa_p \rightarrow \infty$)—we isolate the effect of particle geometry on interface velocity, total undercooling, and surface energy. This is followed by detailed analysis of a dilute binary alloy system, wherein we use a fluorescent solute element to quantify in situ solute segregation effects, revealing how particle curvature (κ_p) modifies local solute fields , constitutional undercooling and final solidification patterns. Finally, introducing deformable air bubbles, in lieu of rigid defects, successfully reproduces defect generation analogous to hot cracking, a critical AM failure mechanism. Ultimately, these experimental results are synthesized into a unified process map that demarcates distinct solidification morphologies based on P_l and v_l, providing a powerful predictive framework for identifying processing windows susceptible to dendritic instabilities and hot cracking.

ABOUT THE SPEAKER

Puli Saikiran is a PhD student in Mechanical Engineering at the Indian Institute of Science (IISc), Bangalore. He works under the guidance of Dr. Koushik Viswanathan at the Laboratory for Advanced Manufacturing and Finishing Processes (LAMFiP). His work primarily focuses on solidification dynamics, metal additive manufacturing, and the development of experimental methods to understand non-equilibrium phenomena.