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Focus on particles

How do laser metal deposition and laser metal fusion actually work? Two simulations help clarify the physical processes involved. The goal? To improve reproducibility and surface quality in both methods.

Particularly when using costly metallic materials, laser additive manufacturing (LAM) is an ideal manufacturing process, as it creates complex 3D parts in near-net shape directly from computer-aided design (CAD) data. In contrast, conventional methods require as-built parts to be finished with machining tools. Despite this unique benefit, broad application of LAM has been impeded because additively manufactured parts still have defects such as porosity and balling, which again can require finishing. Also, the difficulty of predicting dimensional tolerances and the inhomogeneous material properties of final parts hinder extensive industrial usage of LAM.

Overcoming these issues requires a quantitative understanding of the relationship between process parameters, heat transfer, molten metal flow, melt pool shape and solidification microstructure. However, experimental observation of physical phenomena is very difficult, since LAM melt pools are inherently localized and transient. In addition, in situ measurements of thermal and fluid variables using optical and infrared cameras can typically be taken only on the melt pool surface.

> **Thanks to the simulations we finally understand all the relevant process parameters.**

A numerical modeling approach, however, can provide 3D temperature distributions, fluid velocities, melt pool shape and solidification conditions (temperature gradient G and solidification rate R) at any time and location. Unfortunately, many previous numerical simulations that focused on laser or fusion welding processes did not account for the characteristic features of the LAM process in detail.

In the melt pool

Laser metal deposition (LMD) and Laser Metal Fusion (LMF) are both processes that use powder particles and a laser beam to form a deposit layer. The interaction of the laser, powder and substrate must be incorporated into LAM simulations. In LMD systems, the powder particles interact with the laser beam during their flight into the melt pool. The interaction attenuates the power of the laser beam through reflection, absorption and radiation. In addition, the catchment efficiency (= area ratio of melt pool to powder jet) should be accommodated in LMD simulation, since powder particles striking the melt pool are used only to form the deposit layer.

Isolated bulges form in the melt pool during 3D printing.
Figure: Yousub Lee

In LMF systems, the absorbance of the laser beam depends on the configuration of the particles in the powder bed. The melt pool shape, as well as the temperature gradient and fluid flow, are significantly affected by local particle arrangement. Therefore, the effect of powder bed configuration on thermal conditions, surface quality and microstructure should be examined in LMF simulations.

The goal of our simulations was to provide a quantitative understanding of the relationship between the process parameters, thermal conditions, fluid flow, melt pool shape and the resultant microstructure. LMD simulations were performed to show the influence of fluid convection on melt pool shape, solidification microstructure and deposit dimension.

Meso-scale models for LMF were created to show the effect of powder particles and process parameters (i.e. laser power and scanning speed) on melt pool characteristics, particularly temperature profile, melt pool fluid flow, melt pool surface profile and related surface defects. Then, the solidification conditions obtained from the simulation were used to quantitatively assess the solidification microstructure.

Cooling in LMD

For LMD with powder injection, we used a transient 3D transport simulation that took into account the effect of heat transfer, fluid flow, powder particle addition and laser/powder/substrate interaction to investigate the effect of fluid convection on melt pool formation in single-track and single-layer IN718 deposits. The model showed that the most deeply penetrated melt pool was formed at the intermediate region adjacent to the rear melt pool but behind the laser focus spot. This increased melt pool depth occurs due to the impingement of two opposing surface fluid flows induced by the transition of the surface tension gradient from positive to negative along the x-axis.

The predicted melt pool shapes were comparable to experimental measurement in width, height and penetration depth at three different laser powers: 350W, 450W and 550W. The temperature gradient G and solidification rate R were obtained along the melt pool fusion boundary in the model to assess the effect of fluid convection on the solidification microstructure. The cooling rate (G x R) was calculated and the size of the primary dendrite arm spacing (PDAS) was predicted along the fusion boundary using the theoretical models of Kurz-Fisher and Trivedi.

> **» LMD mixes hot melts and cold melts – and that makes exciting things happen.**

The prediction showed that the cooling rate values in the intermediate region decrease not only from greater to lesser depth, but also from the center to the lateral edge of the melt pool boundary. In other words, the general pattern showed that the cooling rate increases with increasing lateral width and depth. The simulation results indicate that the mixing of the two opposing flows in the intermediate region leads to the mixing of hot melt (moving backward from the front of the melt pool)

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and cold melt (moving forward from the melt pool rear).

Consequently, the cooling rate decreases in the region, which corresponds well to the predicted size of the PDAS. Similarly, the predicted size of the PDAS increases near the melt pool lateral edge in the region. The predicted values of PDAS matched well with the measured mean values of 9.9 µm.

Mushroom-shaped bulge

The 3D model explained above was extended to an LMD process with multiple layers on a single track to investigate the influence of fluid convection on melt pool formation and deposit build dimension. Unlike single deposition on a flat substrate, the laser beam and powder particles are projected onto a convex free surface as the layers are stacked. Due to Marangoni shear stress and particle addition, fluid circulation occurs in a melt pool with a convex surface. The simulation showed that the shape of the bottom of the melt pool continually shifts from flat to convex as the build height increases.

Simulations help clarify the physical processes involved in laser metal deposition and laser metal fusion and therefore improve the surface quality.
Picture: Yousub Lee

The analysis at the bottom of the melt pool showed that the convex shape of the melt pool bottom is partially attributable to the convex free surface of the prior layer. Moreover, the investigation of dimensionless numbers (Peclet, Prandtl and Marangoni) and fluid flow patterns showed that Marangoni-driven fluid penetration into the previous layer becomes deeper at the outer edge, thus further intensifying the convex shape of the melt pool bottom. Based on the analysis above, an additional study was carried out with three distinct fluid flow patterns induced by different types of surface tension gradients (positive, negative and mixed), to show their effect on final build geometry.

» **The denser and finer the particles in LMF, the lower the frequency of balling defects.**

A similar mushroom-shaped bulge was observed at the start of deposit build with material that had a positive or negative surface tension gradient. However, when the material had a mixed surface tension gradient, the lateral width of the bulge was reduced by approximately 56% compared to the bulge width of material having a negative gradient. The fluid flow pattern analysis showed that the collision of two opposing flows induced by the mixed gradient is effective in minimizing bulging of the deposit sidewall. Thus, manipulating the surface tension gradient can be an alternative for improving dimensional accuracy and surface finish quality of the deposit sidewall.

Fluid convection in the powder bed

In LMD, the injection of individual particles can be approximated by a lumped mass flux into the melt pool, since the laser beam diameter is about 2 mm, which melts hundreds of powder particles. In contrast to LMD, the ratio of laser beam diameter (100 µm) to particle diameter (20 µm – 40 µm) for LMF is small. Only a limited number of powder particles can be melted at any given time. Therefore, higher resolution of individual powder particles is required for better simulation accuracy.

LMF: 1.) The laser beam strikes the top layer of the powder bed. As it moves to the right the temperature distribution in the melt pool causes the powder to form little islands. These bulges, known as balling, create a "hilly" surface. Parameters supplied by the simulation can help solve this problem.
Picture: Yousub Lee

FA computational framework for LMF was developed in meso-scale resolution. First, a powder bed arrangement was calculated using a discrete element method (DEM) model. DEM accounts for each individual particle as an individual mesh, so the model is able to consider the physical interactions between the particles and the wall. Then, the calculated powder packing information (i.e. locations and radii of individual particles) is exported into a 3D transient heat transfer and fluid flow model as an initial geometry.

The 3D transport melt pool model captures the interactions between the laser beam and the powder particles, particularly free surface evolution, surface tension and evaporation. Therefore, the effect of particle size distribution (PSD), powder packing density, key processing parameters on bead geometry, the occurrence of balling and the solidification microstructure were quantitatively investigated with the 3D model.

Solidification morphology in LMF

The simulation results showed that particle distribution containing a higher fraction of fine particles produced a smoother melt pool contour. It was also found that a higher scanning speed and lower laser power increase the likelihood of balling. The formation of balling defects initiated from a void at the center of the melt pool.

As the void grows, Rayleigh instability causes the melt pool to break into separate islands. Higher packing density is expected to reduce void formation due to augmented mass filling of any new void. In other words, the likelihood of balling occurring can be mitigated by increasing powder packing density.

Furthermore, the solidification conditions (G and R) obtained from the simulation were used to assess the solidification microstructure. The predicted morphology was predominantly columnar and PDAS was estimated to be in the range of 1.32 – 1.87 µm. The calculated solidification microstructure was consistent with experimentally observed morphology and size.

Basis for optimization

The 3D transient transport simulations used above are limited to simple pass or tracks due to the high computational cost. Nevertheless, the models effectively captured essential characteristics of LMD and LMF based on the computation of heat transfer, fluid flow, free surface of the melt pool and solidification microstructure for the LAM process.

Based on our work, we anticipate that the quantitative physical insight from these simulations will enable spatial programming of process parameters to attenuate or accentuate localized microstructures and inhomogeneous material properties during fabrication of LAM parts.

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