Influence of powder wetting on the construction quality of the EBM-printed thin wall structures studied by a multilayer mesoscopic simulation

A. Zakirov, S. Belousov, M. Bogdanova, B. Korneev, I. Iskandarova, A. Perepelkina and B. Potapkin

Kintech Lab Ltd., 123298, Moscow, 3rd Khoroshevskaya st., 12, Russia
e-mail: korneev@kintechlab.com

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Abstract

In the EB-PBF, there is a known set of parameters that have a significant impact on the morphology of a single track, e.g. scan speed, beam width and power, preheating temperature. In this paper we consider the powder wetting as the key parameter to influence on the thin wall morphology. The experimental data available for the laser PBF thin walls is accurately reproduced only if the powder wetting is taken into account. EB-PBF thin wall simulations with varying processing parameters and powder wetting conditions are compared and similar trends are observed. We use KiSSAM Simulation Software for Additive Manufacturing (KiSSAM) to perform a number of multilayer mesoscopic simulations. KiSSAM website: `kissam.cloud`

Physical problem statement

The EB-PBF is a multi-physical and complex process. The following effects are proven to play significant role in the prediction of the manufacturing quality and failures at mesoscopic scale:

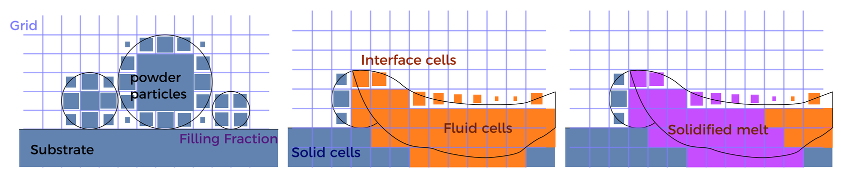
- Melt pool free surface dynamics
  - Surface tension
  - Marangoni convection
  - Recoil pressure
  - *Powder wetting*
- Energy deposition and transfer
  - Electron beam energy input
  - Heat transfer through the powder, the substrate, the melt pool and re-solidified material
- Powder packing
  - Powder particle resolution near the melt pool
  - Powder particles filling factor and distribution

These effects are included in the model used in the current work. For the details please refer to the paper *Zakirov, A. et al. Addit. Manuf. 35 (2020): 101236. https://doi.org/10.1016/j.addma.2020.101236*

Mathematical model

Solid and liquid phases are modelled with Volume of Fluid method. The presence of metal is defined with filling fraction φ.

- $\varphi = 1$ Solid cell;
- $0 < \varphi < 1$ Interface cell;
- $\varphi = 0$ Gas cell.



Also several types of cells are introduces distinguishing the substrate, the particles of the powder bed, the melt and the re-solidified metal.

Electron beam melting simulation

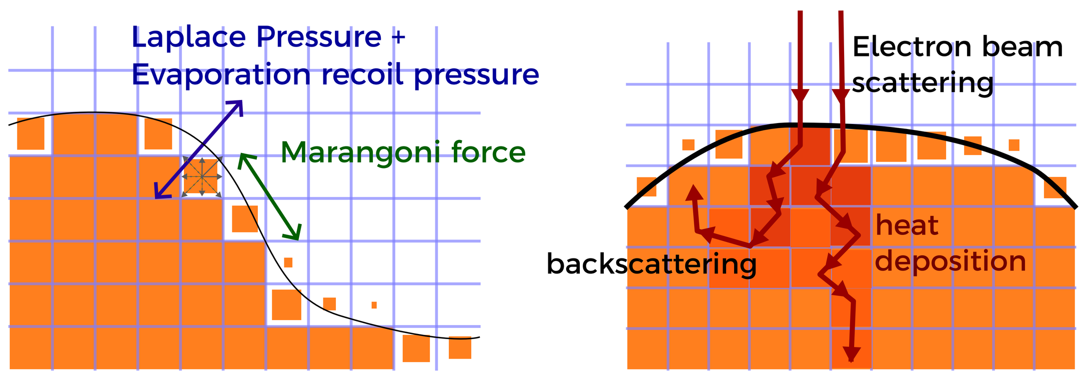
- For the melt pool dynamics simulation, the D3Q27 LBM model and single-relaxation time BGK scheme is used

$$f_i(\vec{x} + \vec{c}_i\Delta t, t + \Delta t) = f_i(\vec{x}, t) - \frac{f_i(\vec{x}, t) - f_i^{eq}(\rho, \vec{u})}{\tau_f} + F_i,$$

where $\vec{c}_i = \{l, m, n\}, l, m, n \in \{0, \pm 1\}, i = 0..26$ are discrete velocity vectors corresponding to the distribution values f_i. F_i is the force term.
The double distribution function (DDF) approach for heat transfer and energy distribution in solid and fluid cells is implemented. On the same mesh, one more set of 27 LBEs is solved:

$$h_i(\vec{x} + \vec{c}_i, t + \Delta t) = h_i(\vec{x}, t) - \frac{h_i(\vec{x}, t) - h_i^{eq}(E, \vec{u})}{\tau_h} + Q_i$$

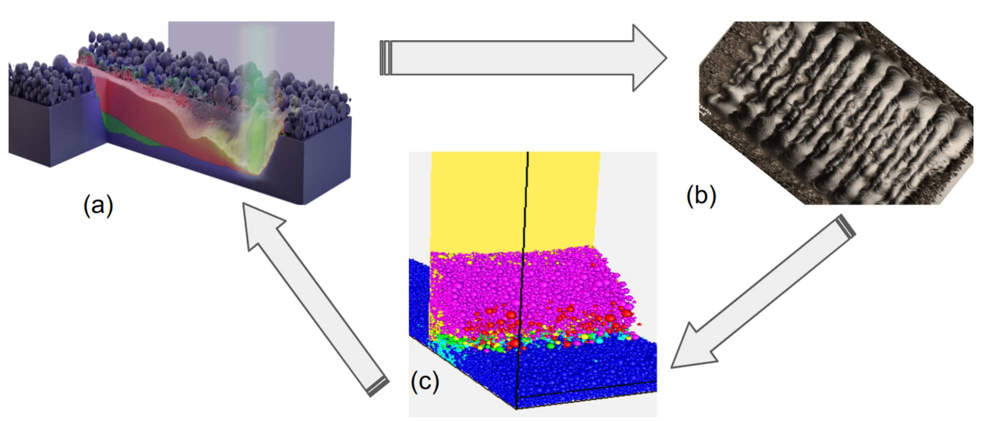
where Q_i is the source term.
Known expressions for the equilibrium values f_i, h_i are used.
- Boundary conditions are implemented, including the free surface effects. Curvature is estimated from the φ field using the template sphere approach with the wetting effects included. The heat gradients generates Marangoni convection, which is included as a tangential force on the surface. Evaporation is calculated by the Knight model, and the recoil pressure is included.



- Monte Carlo scattering is implemented for the electron beam source simulation. The rays are scattered in the material, and deposits energy along the path. Backscattering is included in the numerical model.
- The heat transfer is modelled in fluid, interface, and solid cells using the DDF LBM in the melt pool grid. Heat equation alone is solved far from the melt pool on a tractile mesh. On the material surface, the radiation heat loss is implemented. Convective cooling of spatters is implemented as well using the Whitaker model.

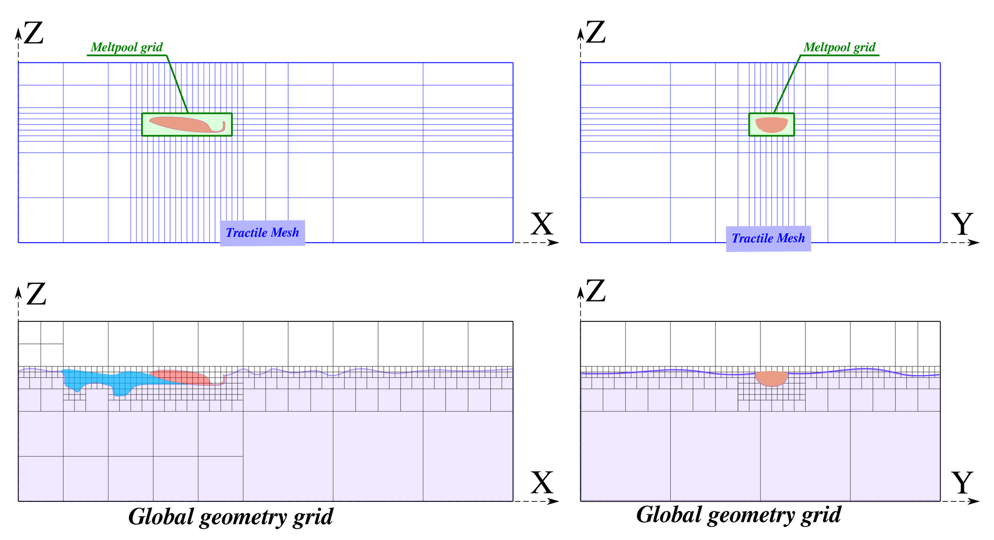
Powder packing simulation

- The discrete element method (DEM) is used for the accurate prediction of the powder packing distribution. A GPU DEM solver is used, based on the open-source Blaze-DEMGPU software with massive in-house add-ons for the PBF simulations.



- The multilayer EB-PBF simulation takes place as follows. After the layer is simulated in the LBM module (a), the new solidified surface is generated (b). This surface is loaded into the DEM module and used as the substrate for the particles deposition (c). The resulting particle cloud, in turn, used for the simulation for the next layer (a).

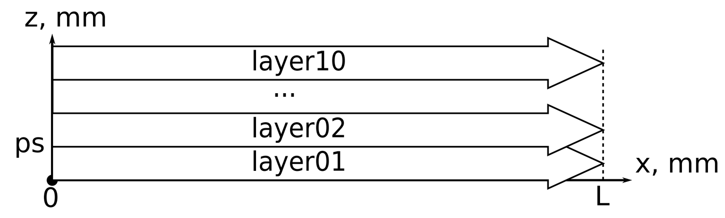
High performance implementation



- Adaptively rebuilt non-uniform structured mesh is used, with the finest melt pool grid and the tractile surrounding mesh.
- The global geometry including the substrate surface and the powder particles are stored in adaptive VDB format.
- Both LBM and DEM solvers are GPU-implemented. The powder packing simulation for 1 layer is $\lesssim 1$ hour, while the PBF simulation time is about 1 hour per 1 ms of simulated process.

Simulation setup

The walls having the single track width and the ten layer height are built with the identical beam scan strategy at each layer. The build is schematically shown on the right. The platform step ps and the wall length L is specified further.



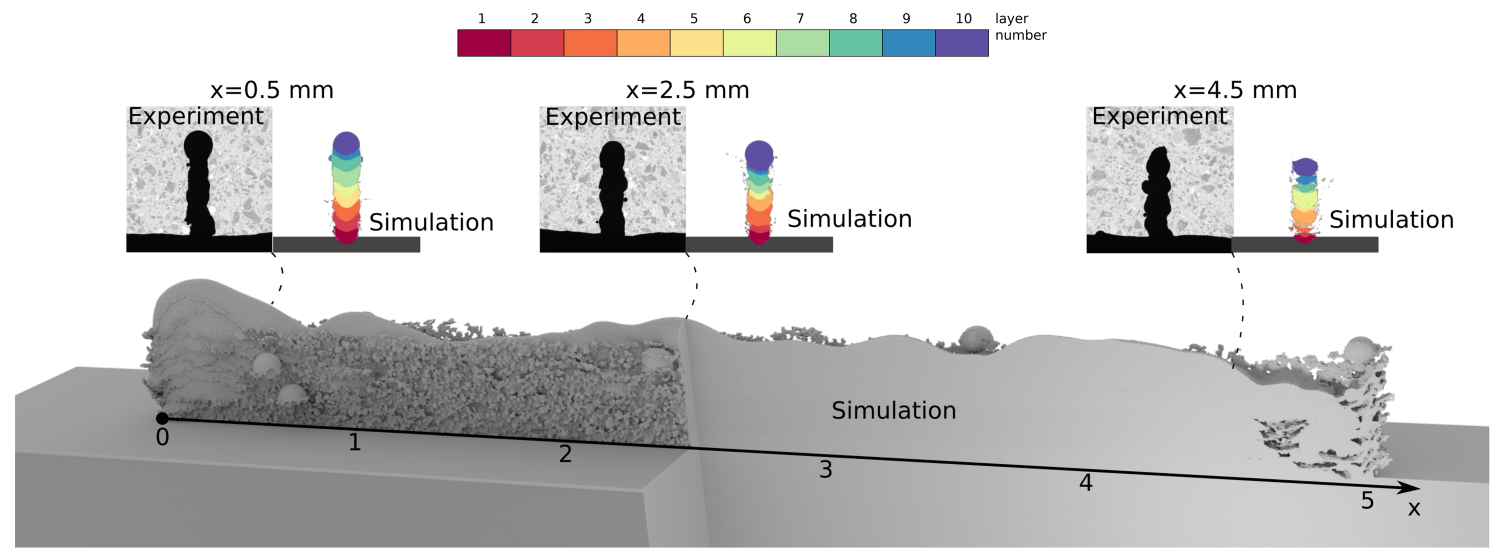
Ti6Al4V is selected for the EB simulations. Several processing parameters are chosen for the case study. They are arranged in the following table.

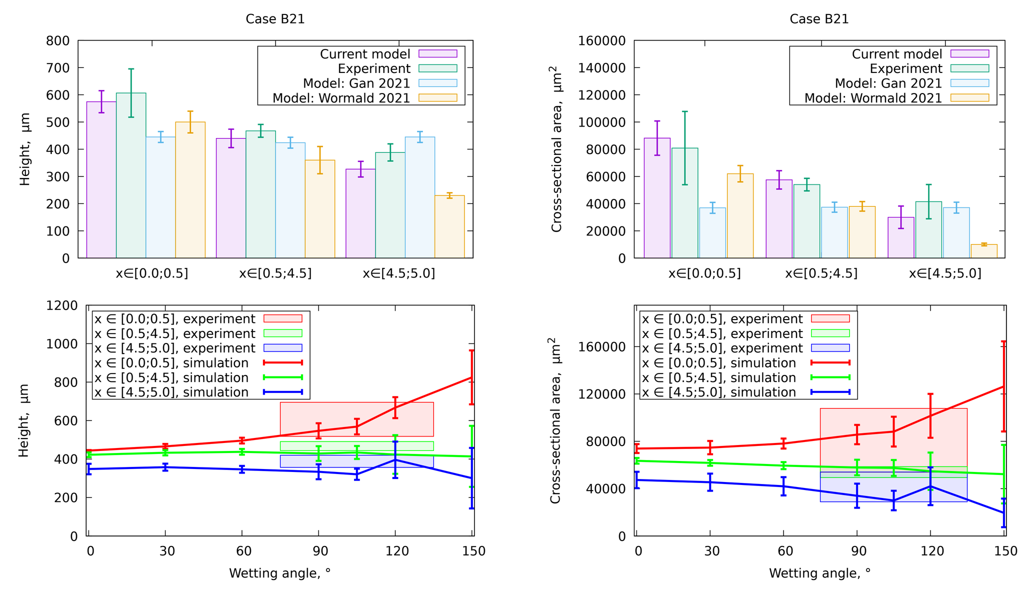
Case ID	Power, W	Velocity, m/s	D4σ, μm	Track length × number of layers	Platform step, μm
1	1700	4.3			
2	2000	4.3	900	8 mm × 10	50
3	1200	5.0			

Powder size distribution size is 40–100 μm. The discretization steps are equal $\Delta r = 5\mu$m, $\Delta t = 75$ ns. Full domain size is 10 mm × 2 mm × 3 mm, substrate thickness is 2 mm.

Validation of thin-wall simulations

Validation of multilayer thin wall builds was carried out using the experimental data of Air Force Research Laboratory (AFRL) Additive Manufacturing (AM) Challenge Series (the Challenge). $ps = 0.04$ mm and $L = 5$ mm in the experiment. Inconel 625 was used. Details on the experiment can be found in the paper *Schwalbach, E. J. et al. Integr. Mater. Manuf. Innov., 10(3), 319-337. https://doi.org/10.1007/s40192-021-00220-9.*



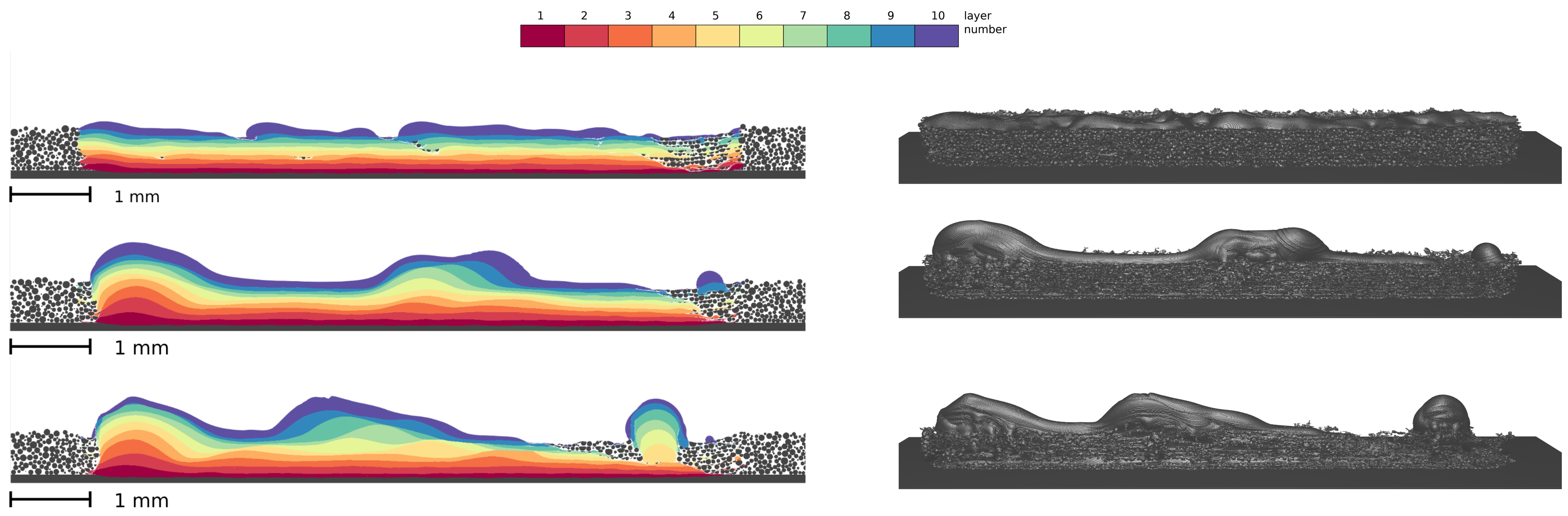


Our model gives very accurate predictions of the thin-wall morphology both in qualitative and quantitative points of view. The thin wall morphology appears to be very strong-dependent on the powder wetting equilibrium angle θ_{pow}. The wall width decreases with the increase of θ_{pow} while the wall height variation and the height in the beginning increases. The paper on this research is submitted in Additive Manufacturing.

Results

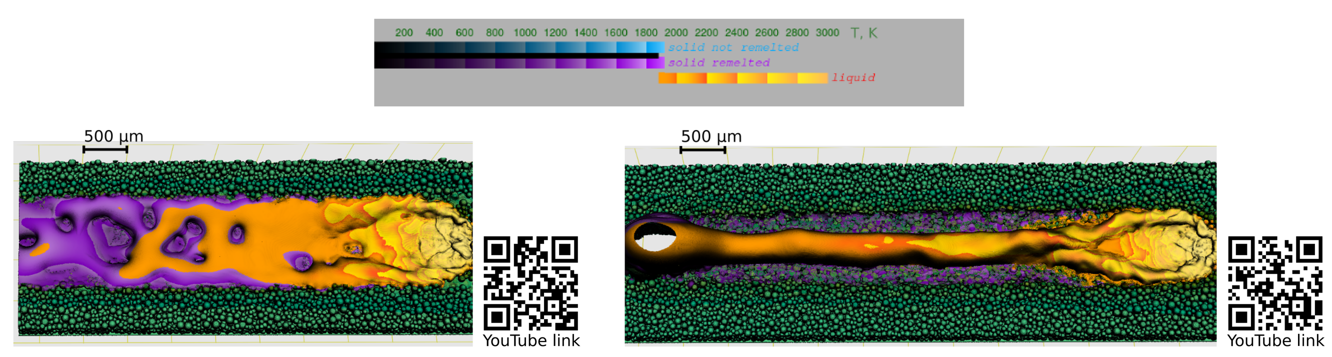
The results above were obtained for the L-PBF, which characterized with smaller spot sizes and other process scales compared with the EB-PBF. So for the EB thin walls we take $ps = 0.05$ mm and $L = 8$ mm.

The wetting angle between the melt and the powder θ_{pow} was varied in a wide range. Below the simulation results are shown for the Case 1 and $\theta_{\mathrm{pow}} = 30°$ (top), $\theta_{\mathrm{pow}} = 90°$ (middle) and $\theta_{\mathrm{pow}} = 120°$ (bottom).



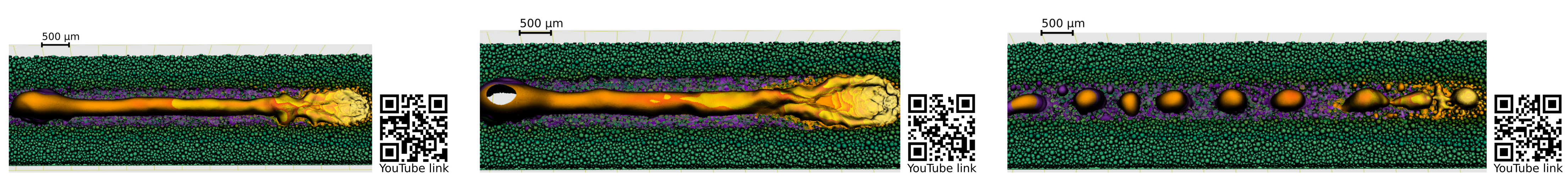
It is shown that the θ_{pow} parameter strongly influences on the wall height and height variation along the wall profile.

Also the wall width decreases with θ_{pow}. It could be explained by studying the melt pool dynamics.

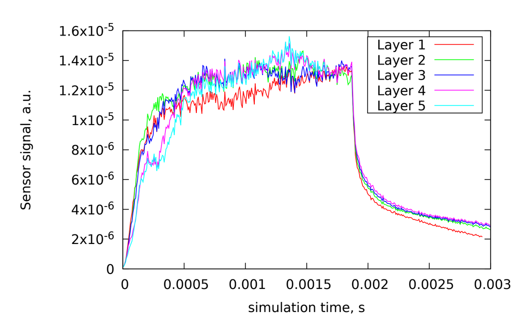


The figure above is a top view of the melt pool during the simulation for the Case 2. If good wetting is set (left figure, $\theta_{\mathrm{pow}} = 10°$), the melt pool widens and shortens. Setting $\theta_{\mathrm{pow}} = 90°$ leads to the narrowing and elongation of the melt pool.

The figure below shows the top view of the melt pool during the simulation of the wall builds for the cases 1 (left), 2 (middle) and 3 (right). Cases comparison shows that increasing the EB energy density (ratio of the EB power to its velocity) leads to a slight increase in the wall width. Smaller EB energy density increases the risk of the track discontinuities due to the balling effect.



Sensor data simulation



Photodiode sensor signal is simulated during the multilayer simulation. This data could be used for advanced sensor response and feedback algorithms development, including the machine learning algorithms.

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Conclusions

An approach to the simulation of a whole additively manufactured mesoscopic thin wall detail is presented based on the high-performance high-fidelity KiSSAM software. It is shown that the powder wetting might be a key factor explaining the wall morphology features. Simple approximation of the wetting by a constant equilibrium wetting angle provides adequate results and it might be improved by taking the temperature dependency and chemical composition into account. The proposed approach is applicable for the predictive simulation of thin-walled and other fine structures.