SIMULATION OF ADDITIVE MANUFACTURING PROCESS

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Nov 2021

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    - ITP strategy

Main AM process characteristics

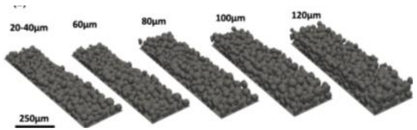
$$\nabla \cdot \boldsymbol{u} = 0$$

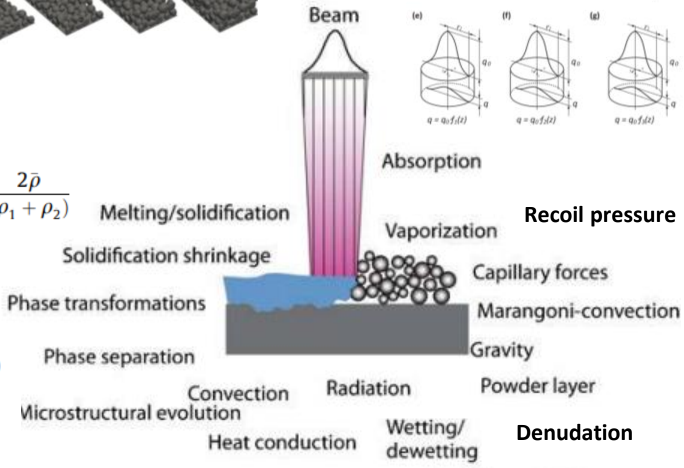
$$\begin{aligned}
&\frac{\partial \bar{\rho}\boldsymbol{u}}{\partial t} + \nabla \cdot (\bar{\rho}\boldsymbol{u} \otimes \boldsymbol{u}) \\
&= -\nabla p + \nabla \cdot \bar{\bar{T}} + \bar{\rho} g \hat{\boldsymbol{e}}_z \beta (T - T_{ref}) - K_C \left(\frac{(1-f_L)^2}{f_L^3 + C_K} \right) \boldsymbol{u} \\
&\quad + \left[\sigma \kappa \hat{\boldsymbol{n}} + \frac{d\sigma}{dT} (\nabla T - \hat{\boldsymbol{n}}(\hat{\boldsymbol{n}} \cdot \nabla T)) + \hat{\boldsymbol{n}}(p_V \mathrm{II} \cdot \hat{\boldsymbol{n}}) \right] |\nabla \alpha_1| \frac{2\bar{\rho}}{(\rho_1 + \rho_2)}
\end{aligned}$$

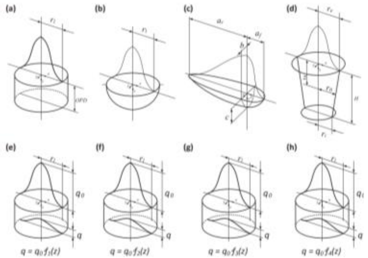
$$\bar{\bar{T}} = 2\bar{\mu} \left[\left(\frac{1}{2} \nabla \boldsymbol{u} + \frac{1}{2} (\nabla \boldsymbol{u})^T \right) - \frac{1}{3} (\nabla \cdot \boldsymbol{u}) \mathrm{II} \right].$$

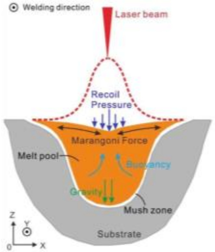
$$\begin{aligned}
\frac{\partial \bar{\rho} \bar{C}_p T}{\partial t} + \nabla \cdot (\bar{\rho} \boldsymbol{u} \bar{C}_p T) = &-\frac{\partial \bar{\rho} \Delta H_f}{\partial t} - \nabla \cdot (\bar{\rho} \boldsymbol{u} \Delta H_f) + \nabla \cdot (\bar{k} \nabla T) \\
&- [(h_c (T - T_{ref}) + \sigma_s \epsilon (T^4 - T_{ref}^4) \\
&+ Q_V) |\nabla \alpha_1| - Q_T] \frac{2 \bar{C}_p \bar{\rho}}{(\bar{C}_{p1} \rho_1 + \bar{C}_{p2} \rho_2)}
\end{aligned}$$

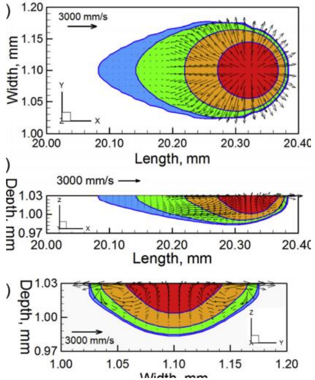
$$Q_T(r,z) = \frac{\zeta \eta q_{\text{laser}}}{\pi (1 - e^{-3})(E + F)} \left(\frac{1 - \chi}{z_e - z_i} z + \frac{\chi z_e - z_i}{z_e - z_i} \right) \exp \left(-\frac{3r^2}{r_0^2(z)} \right)$$

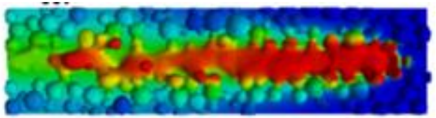


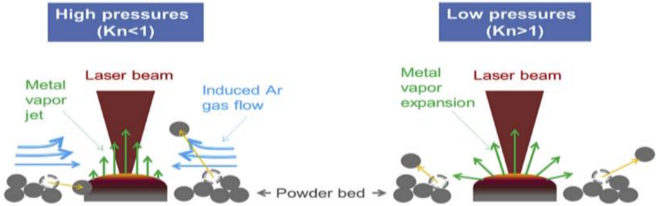












Thermo-Mechanical => residual stress & distortions

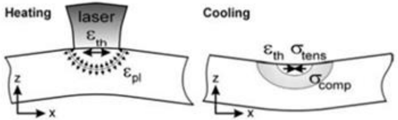
The additive manufacturing (AM) process involves heating, melting and solidification of an alloy by a moving heat source such as a laser or an electron beam in a layer by layer manner [1,2]. As a result, different regions of the work piece experience repeated heating and cooling [2]. The spatially varied thermal cycles result in residual stresses and distortion in the additively manufactured components [3]. Tl

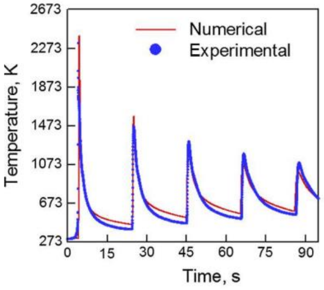
In principle it is possible to simulate the thermo-mechanical problem by solving the heat transfer problem plus the material mechanical problem with non linear plasticity models to capture the residual stresses and deformations.

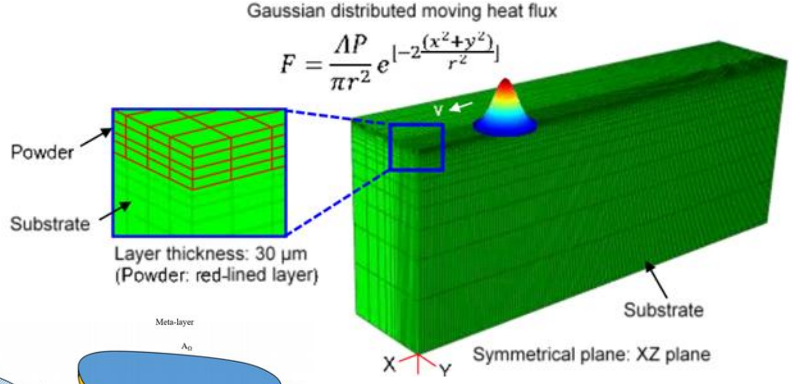
The extreme rapid heating close to laser surface first produce a local expansion which is inhibited by surrounding cooler material hence generating a compression layer well beyond yield limit. After top layer cool down material tends to contract which is inhibited by underlying material hence generating traction residual stresses

However due to the extremely thin bed layers and small scan laser tracks **it is not viable to simulated the process** at the real scale and try to integrate up to the part scale
Therefore => **an aggregation strategy for laser scan layers and width is needed to compute full thermo-mechanical field at full part scale which has to be validated**

Figure 1 TGM inducing residual stress







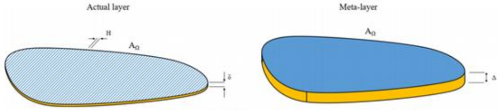
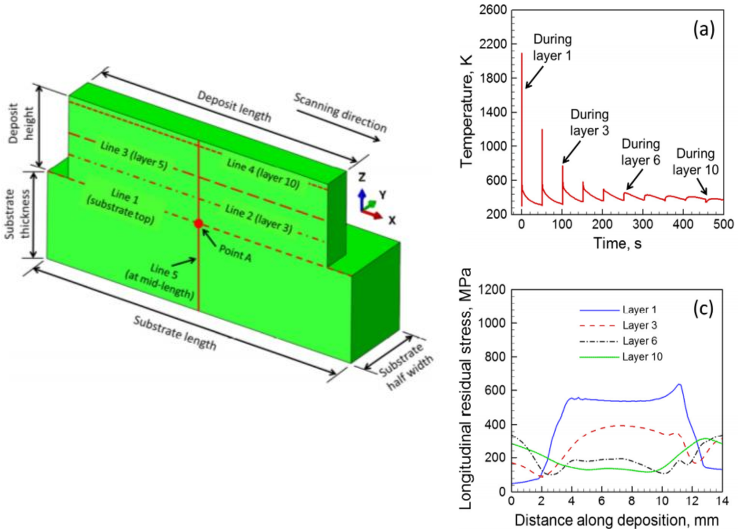


Fig. 6. (Left) Actual layer (with thickness δ) and (right) meta-layer (with thickness δ). H is the hatch distance.

Thermo-Mechanical



Also the **effect of separation of the base plate and Heat Treatment for stress relief is needed to predict final distortions of part**

This can be solved by **conventional FEM with right creep modellization**

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Residual stresses and distortion in additively manufactured compositionally graded and dissimilar joints

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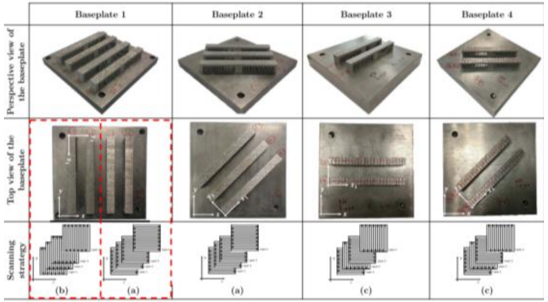
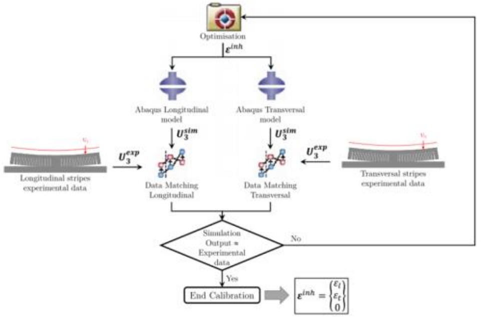
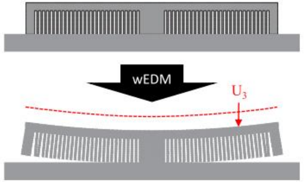
Mechanical (Inherent Strains)

. It allows for replacing computationally costly thermo-mechanical simulations by a linear-elastic-mechanical one. The key point in this simplified analysis is to define which is the inherent strain or shrinkage load to apply in the model in order to capture the mechanical response of the fabricated component.

There are two approaches to determine these inherent strains as proposed in CWM [27]: (a) Multi-scale or local–global modelling; (b) Empirical approach.







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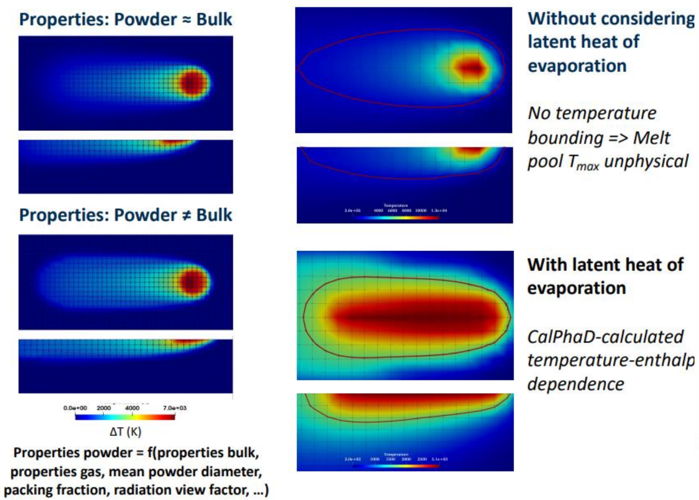
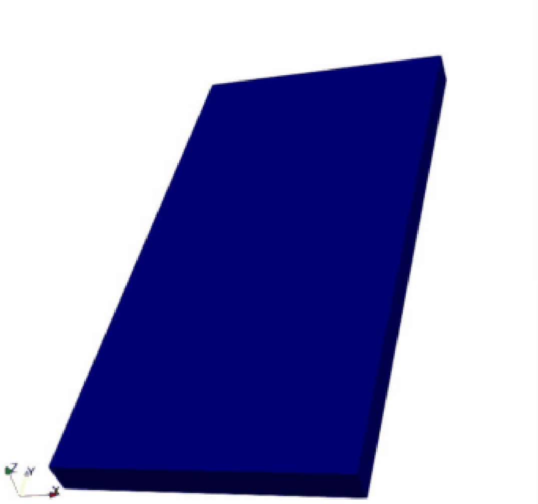
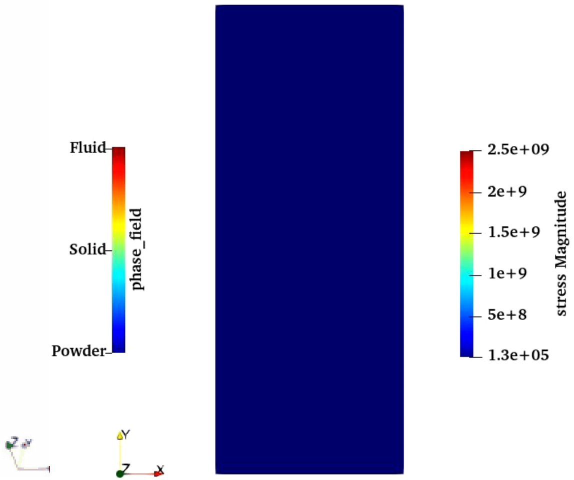
Empirical methodology to determine inherent strains in additive manufacturing

Iñaki Setien [a,*], Michele Chiumenti [c,d], Sjoerd van der Veen [b], Maria San Sebastian [a], Fermín Garciandía [a], Alberto Echeverría [a]

Thermo-Mechanical => ITP Strategy (collaboration wit IMDEA)







In Validation phase

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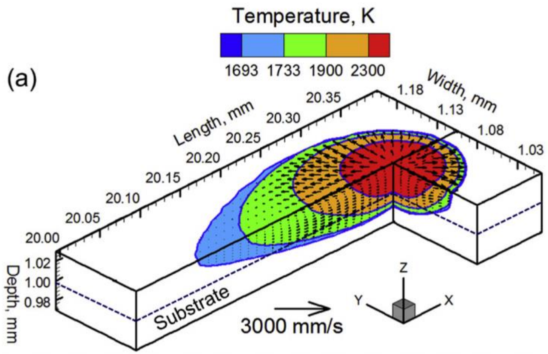
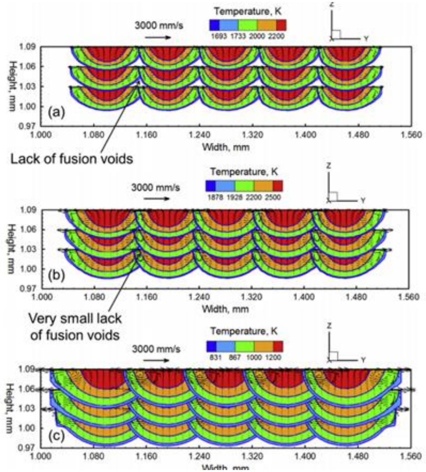
Thermo Fluid (melt Pool)

Phase change and melt pool fluid dynamics is of high complexity with significant unique phenomena
This is all at meso scale that can not be simplified or aggregated at larger scale if associated defects are to be predicted

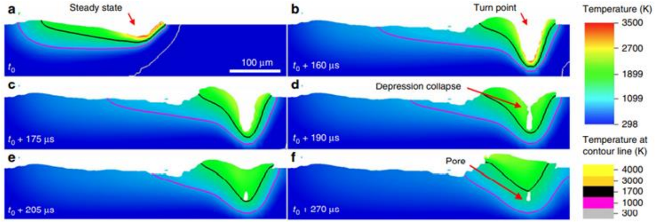
Marangoni effect generated due to surface tension due to temperature gradient must be imposed at the melt pool free surface as boundary condition (1000 times larger than buoyancy force)



Lack of Fusion



Pores



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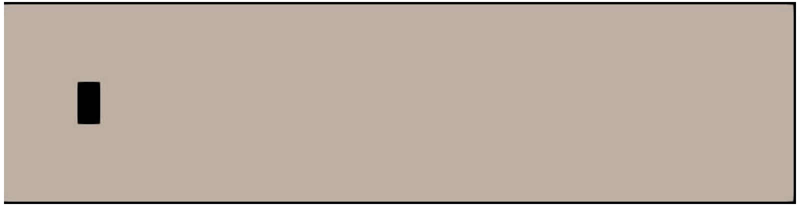
Thermo Fluid (Melt Pool) LoF & Pores ITP Strategy (collaboration with IMDEA)

LBM ITP code in WIP

In principle LBM seems to be the perfect candidate to simulate the dynamics of Melt Pool
- High Fidelity incompressible fluid flow
- Inherently transient
- Free Surface tracking
- Phase Change prediction capability
- Two Phase Flow capability
- Opportunity to implement Heat Transfer terms

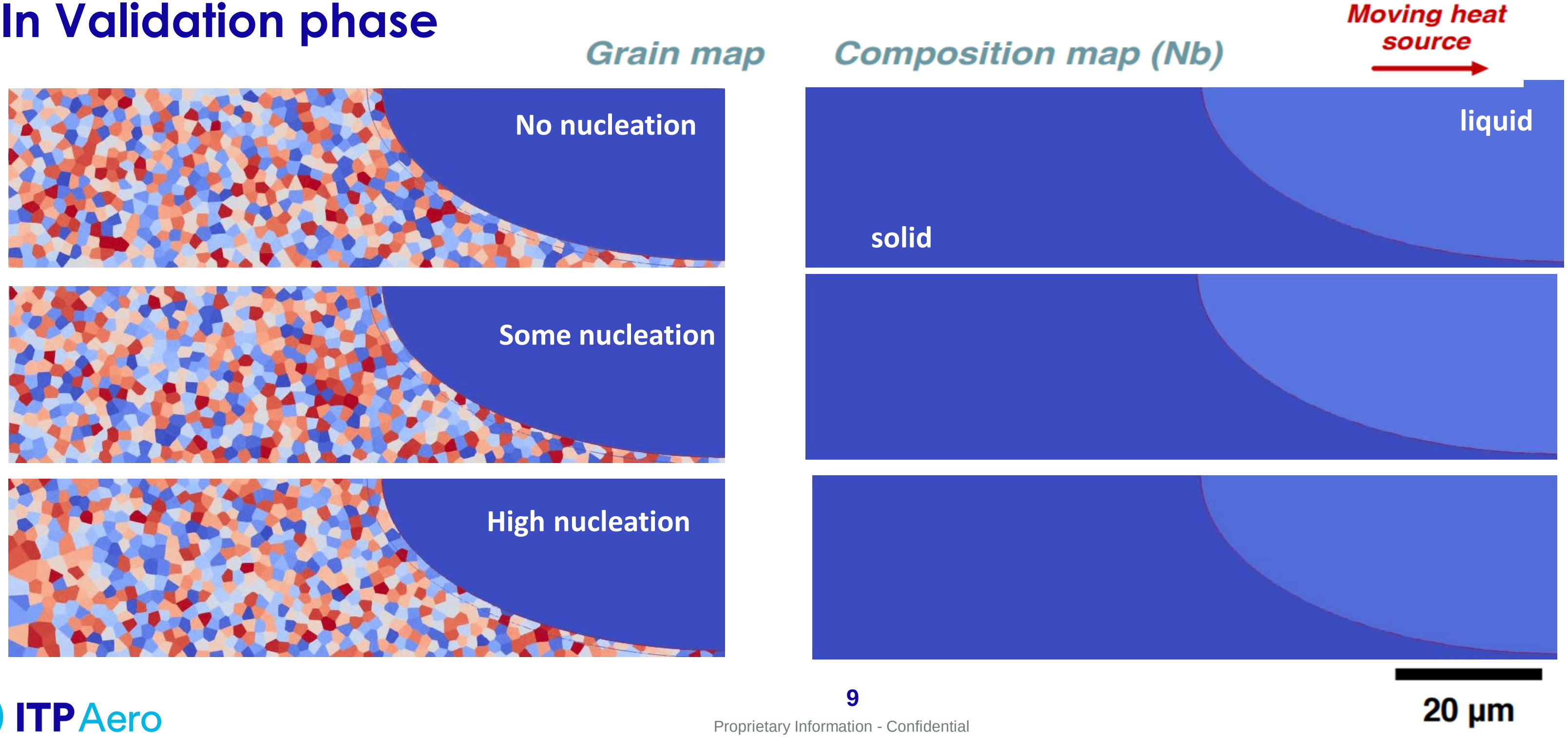


Risks:
- Difficulties with high density ratios of phases (≈ 1000)
- Potential impossibility to recover some equation terms (radiation, Marangoni …) ¿?

Material (Microstructure, properties) ITP strategy (colaboration with IMDEA)

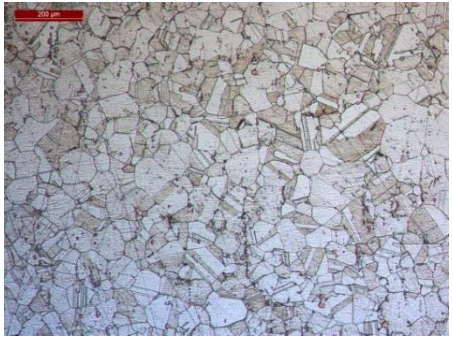
Simulation of grain growth competition, dendritic structure within grains, solute segregation

In Validation phase

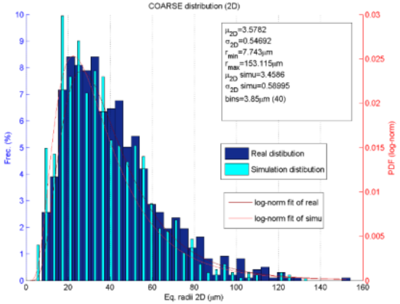


Material (Microstructure, properties) ITP strategy (colaboration with IMDEA)

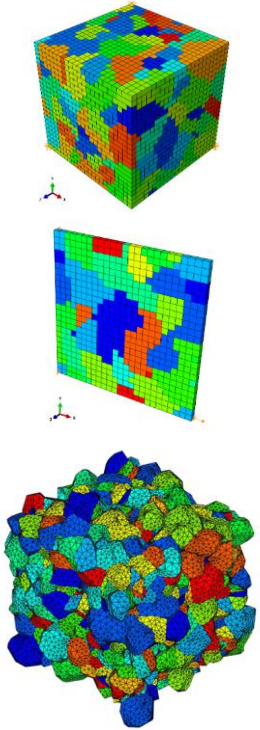
Microstructure



Grain Size distributions



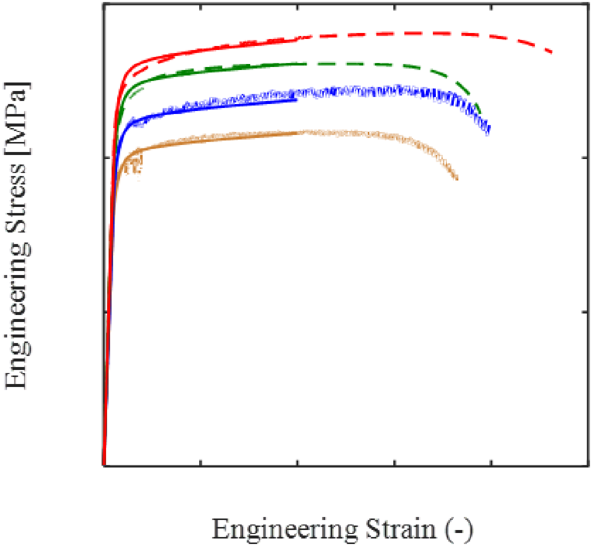
RVE: representative volume elements



MICROMECH: Microstructure sensitive material mechanical models, 718 alloy wrought

Cristal plasticity models & prediction of monotonic behaviour (tensile curves)

Strength as a function of microstructure & temperature



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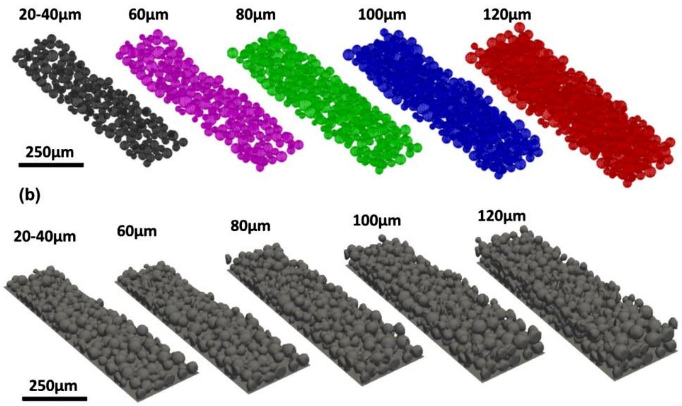
Surface morphology

To simulate the position and arrangement of powder particles with a representative size distribution in a layer, a method, proposed by Zhou et al. [18], which involves dropping particles following a trajectory based on the geometry of the objects encountered has been adopted and modified. This approach ignores the motion of obstacles encountered by the falling particles and the trajectory of a particle is determined based on the number of obstacles being encountered. Several potential obstacles and corresponding trajec-

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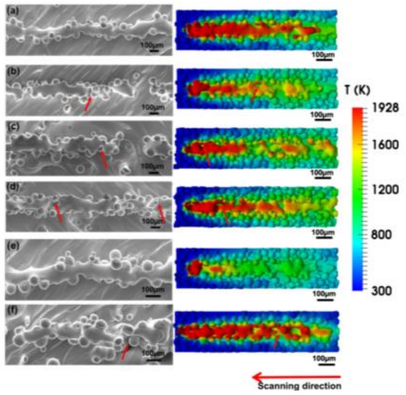
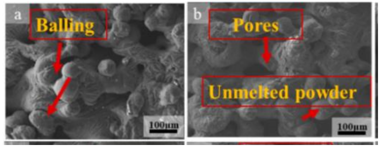
Mesoscale modelling of selective laser melting: Thermal fluid dynamics and microstructural evolution

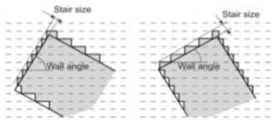
Chinnapat Panwisawas [a,*], Chunlei Qiu [a,b], Magnus J. Anderson [a], Yogesh Sovani [a], Richard P. Turner [a], Moataz M. Attallah [a], Jeffery W. Brooks [a], Hector C. Basoalto [a,*]

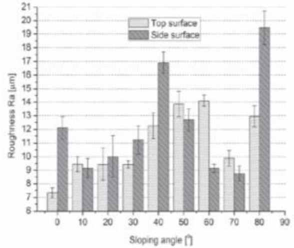
[a] School of Metallurgy and Materials, University of Birmingham, Birmingham B15 2TT, UK
[b] School of Engineering, Cardiff University, The Parade, Cardiff CF24 3AA, UK

To further investigate the thermal fluid flow characteristics giving rise to surface structure, porosity development and microstructure simulation, a computational fluid dynamics (CFD) calculation using the C++ open source CFD toolbox so-called Open Field Operation and Manipulation (OpenFOAM®) has been developed to model the interaction between the laser heat source and the randomly distributed Ti-6Al-4V powder materials, which is illustrated in Fig. 3(b). In the model, all interfacial phenomena, including surface tension (capillary force), Marangoni's flow (thermo-capillary force), recoil pressure, drag force due to solid/liquid transition via Darcy's term, and buoyancy force, present within the SLM process have been included in simulation. The energy dissipation in the





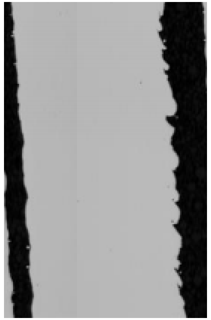


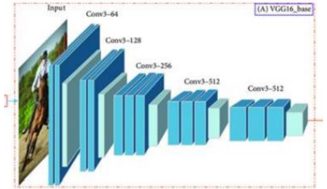


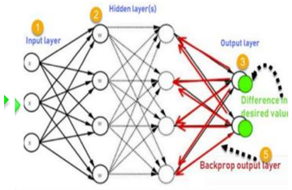
Surface morphology
ITP strategy

Surface LoF

Surface Roughness







Real Case
Probability of Defects
Modification of parameters
for minimum probability

Future plans consider to develop and validate dedicated AI augmented simulation tools to be able to predict defects and optimize parameters to further avoid any detrimental surface conditions

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