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Multi-scale and Multi-physics Numerical Simulations in Powder-based Additive Manufacturing Technologies

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Abstract

Metallic additive manufacturing (AM) or 3D printing is the process by which metal parts are joined or solidified from feedstocks such as blown powder (Direct Energy Deposition-DED) or powder bed (Selective Laser Melting-SLM, Electron Beam Melting-EBM). AM has begun to revolutionize many industries such as aerospace, automotive, or bio-medical by providing unlimited freedom of design, mass customization, waste minimization, and the ability to fabricate highly complex structures. However, extremely complex physical phenomenon behind the process of those above-mentioned technologies make the selection of optimal process parameters to obtain and control the fabrication of 3-D parts become the biggest challenge in AM. Trial-and-error experimental approach is both time-consuming and resource-consuming. Hence, numerical simulation is widely recognized to be the weapon of choice for researchers to reveal the physics behind the process and to optimize the process parameters selection. Along with sophisticated monitoring systems and machine learning technologies, numerical simulations are contributing in making AM the new era of manufacturing.

Research Focus

Electron Beam Melting (EBM)

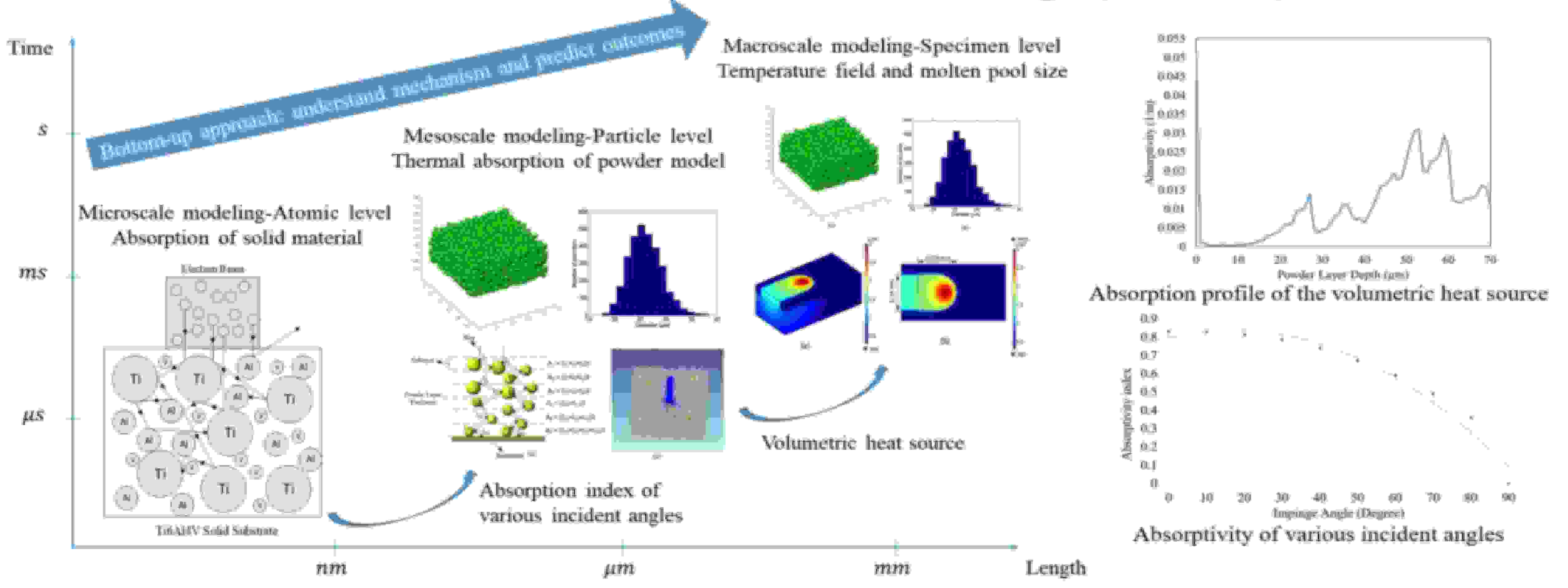

Fig. 1. Multi-scale simulation framework for single-track scan of EBM process [1].

As shown in Fig. 1, the ray-tracing simulation starts at the microscale (the atomic level). The absorption index is utilized as the input to the Monte Carlo ray-tracing at the mesoscopic level (i.e., the powder-particle level) to derive the depth profile of the absorbed electron energy in a Ti6Al4V powder layer of a known size distribution. Then, the corresponding volumetric heat source is derived and used as the input to the heat-transfer finite-element (FE) simulations using COMSOL Multiphysics

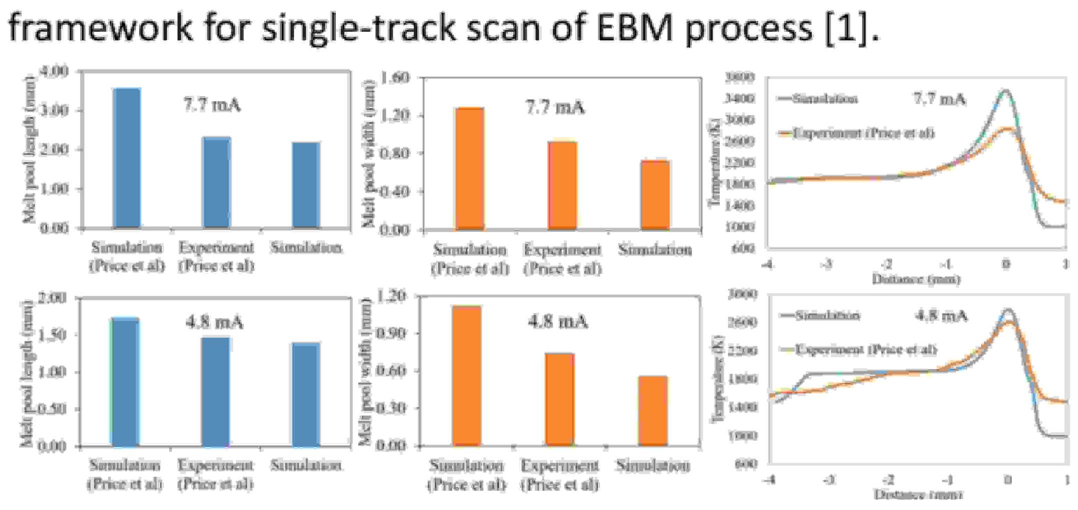

Fig. 2. Simulated melt-pool dimensions and temperature distribution in comparision with reference [1].

Price, S., Cheng, B., Lydon, J., Cooper, K., & Chou, K. (2014). On process temperature in powder-bed electron beam additive manufacturing: process parameter effects. Journal of Manufacturing Science and Engineering, 136(6), 061019.

Direct Energy Deposition (DED)

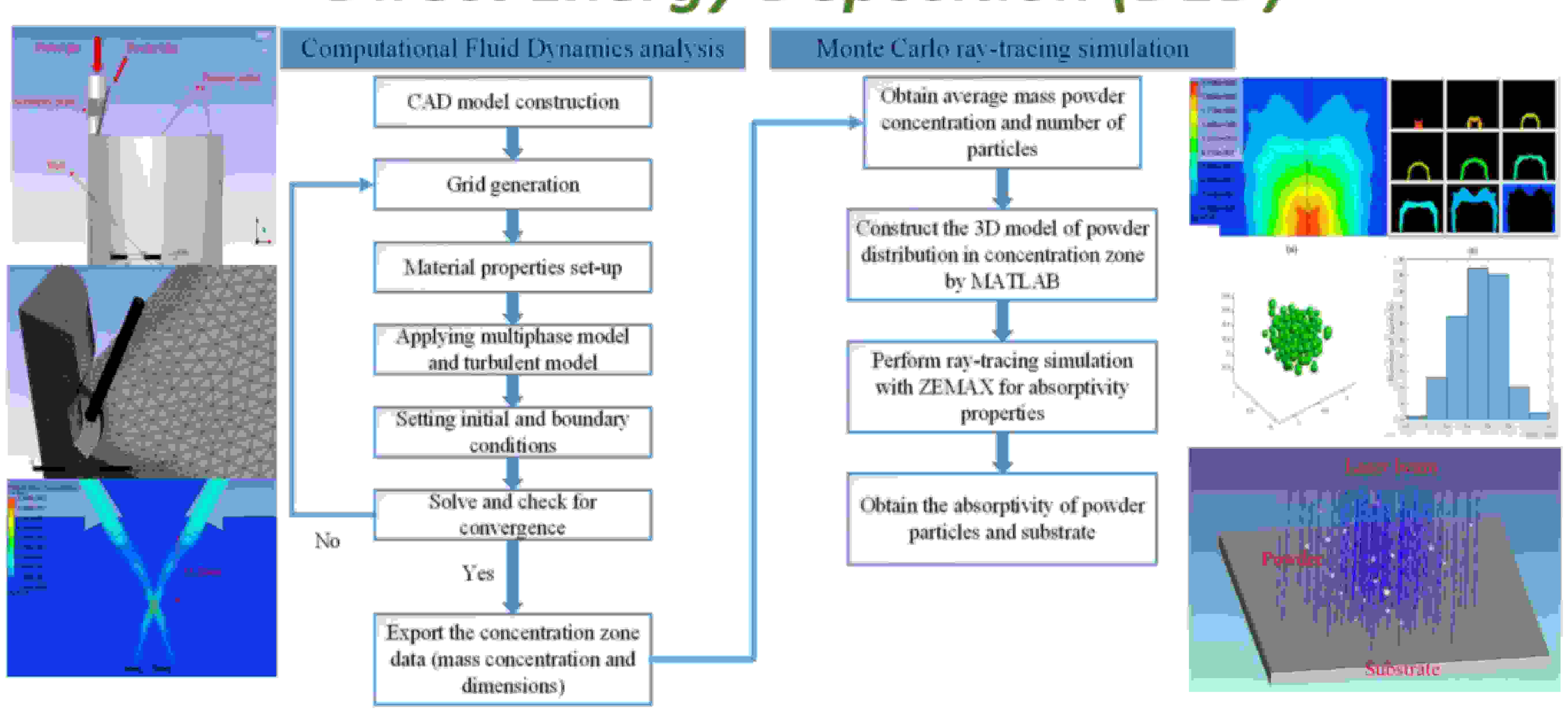

Fig. 3. Schematic diagram of proposed modeling framework of laser absorptivity analysis in DED process [2].

The present study proposes a systematic approach for calculating the absorptivity of the laser radiation in the DED process. In the proposed approach, Computational fluid dynamics (CFD) simulations are first performed to establish the dimensions and location of the powder concentration region. Then, Monte Carlo ray-tracing simulations are performed to calculate the total powder energy absorptivity of the concentration region. Overall, the results presented in this study provide a useful insight into the initial thermal and state conditions of the powder particles entering the melt pool. As such, the proposed modeling approach plays an important role in performing high-fidelity numerical simulations of the DED process.

Selective Laser Melting (SLM)

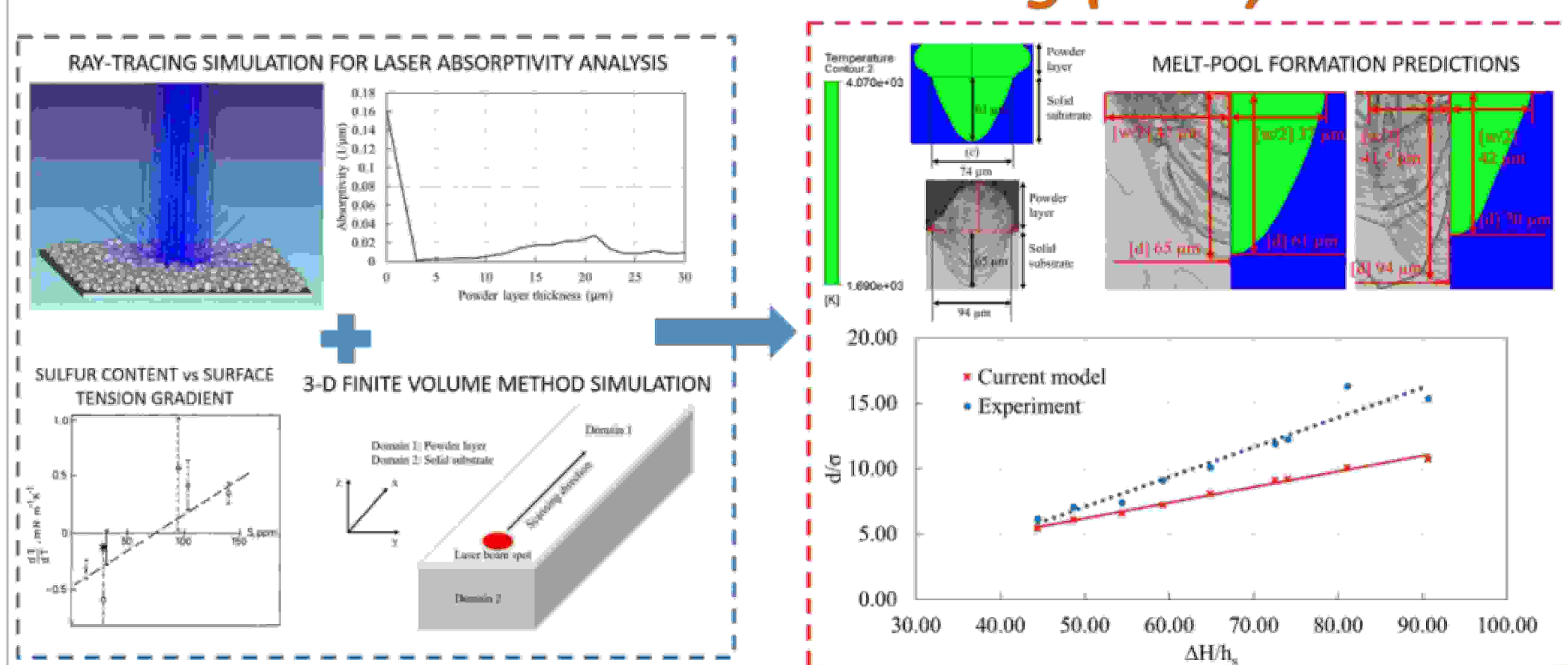

Fig. 4. Schematic diagram of the heat-and-mass transfer numerical model for SLM process [3].

A three-dimensional thermal-fluid model is constructed to investigate the effects of Marangoni convection on the melt-pool formation during the Selective Laser Melting of SS316 powder. The model takes account of the heat-and-mass transfer effects and the melt-pool flow dynamics. In the model, the surface tension gradient in the melt-pool is estimated as a function of the sulfur content of the metal powder based on the reported experimental data. The results show that besides the conduction mode, in which the melt-pool formation is dominated by thermal conduction, and the keyhole mode, in which the melt-pool formation is determined mainly by the recoil pressure, an additional transition mode exists between these two modes, in which the melt-pool formation is driven mainly by the Marangoni convection effect. In particular, for stainless steel powders with a higher sulfur content, an inward Marangoni flow occurs, which results in a deeper melt-pool and a lower porosity of the built part.

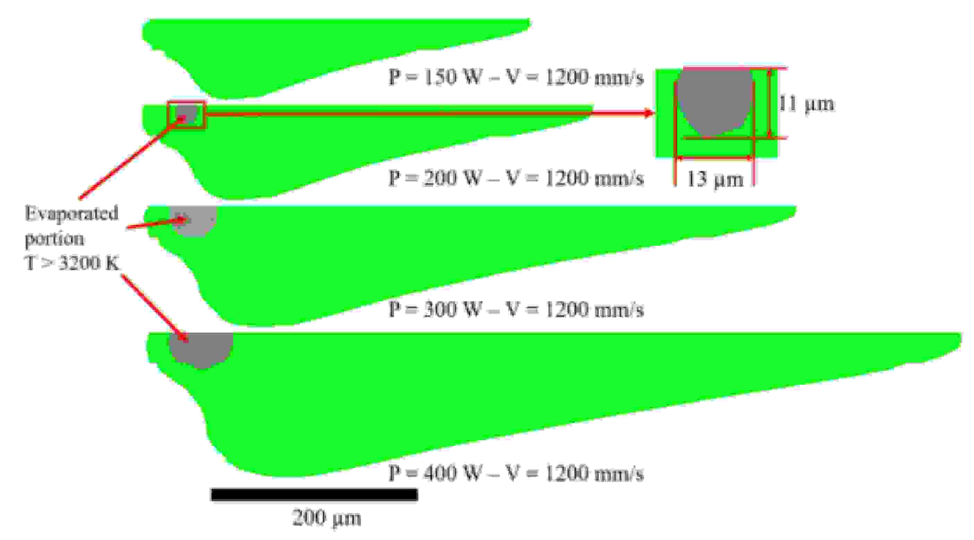

Fig. 5. Side-view images of simulated melt-pools produced with scanning velocity of V = 1200 mm/s and laser powers in range of P = 150–400 W [3].

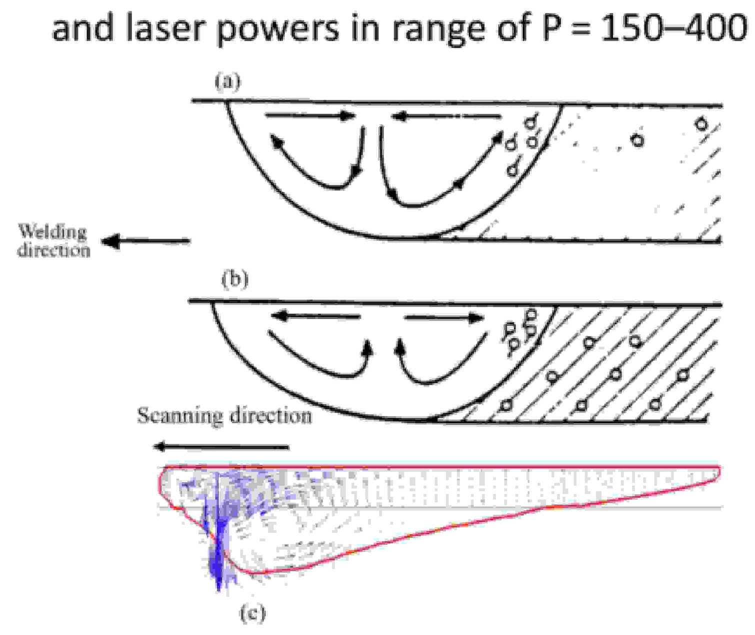

Fig. 6.Effects of weld pool motion on porosity: (a) inverse Marangoni flow; (b) conventional outward Marangoni flow [3].

References

[1] **Le, T. N.**, Lo, Y. L., & Tran, H. C. (2019). Multi-scale modeling of selective electron beam melting of Ti6Al4V titanium alloy. The International Journal of Advanced Manufacturing Technology, 1-19.

[2] Jhang, S. S., Lo, Y. L., & **Le, T. N.** (2019). Systematic modeling approach for analyzing the powder flow and powder energy absorptivity in direct energy deposition system. The International Journal of Advanced Manufacturing Technology, 1-12.

[3] **Le, T. N.**, & Lo, Y. L. (2019). Effects of sulfur concentration and Marangoni convection on melt-pool formation in transition mode of selective laser melting process. Materials & Design, 179, 107866.

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