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## CFD Simulations for Additive Manufacturing Processes

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### Abstract

Computational fluid dynamics (CFD) modelling helps with development of process windows for various additive manufacturing processes such as laser powder bed fusion (LPBF), selective electron beam melting (SEBM) and direct energy deposition (DED). CFD models, which are based on a rigorous solution of the conservation equations, incorporate important underlying phenomena such as laser/electron beam with powder interaction, melt pool dynamics, phase change and solidification. Once calibrated against experimental data, these models provide insights into how process parameters such as beam power, scan speed, hatch spacing, powder size distribution, and powder compaction affect melt pool quality, porosity formation, balling defects, and microstructure evolution. Case studies from the industry and academia highlighting the successful use of CFD models in developing process windows for different AM processes are discussed in this presentation. Such high-fidelity, multiphysics CFD models provide a framework to better understand AM processes from the micro- and meso-scales.

Keywords: CFD simulations, laser powder bed fusion process, FLOW-3D, melt pool dynamics, direct energy deposition

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### 1. Introduction

Laser welding has been replacing traditional welding methods due to its superior productivity, faster scan speeds and lower heat inputs. With better control and smaller heat affected zones, laser processing technology has led to a rise of interest in metal additive manufacturing (AM) processes such as laser powder bed fusion and direct metal deposition.

Although AM has been generating significant interest, challenges remain towards a more widespread adoption of this technology. These challenges include defect formation such as porosity and spatially non-uniform material properties that occur because of insufficient knowledge of process control. Computational fluid dynamics (CFD) modelling can help researchers understand the effects of process parameters on underlying physical phenomena such as melt pool dynamics, phase change and solidification. With experimental studies successfully capturing melt pool data such as molten metal velocities and temperatures, it is possible to calibrate numerical models using experimental data. These numerical models,

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which are based on a rigorous solution of the conservation equations, can provide further insights such as fluid convection in the melt pool, temperature gradients and solidification rates.

In this paper, case studies from industry and academia highlighting the use of CFD and numerical models in understanding powder bed fusion processes are discussed. Process parameter optimization in controlling porosity formation and balling defects for the IN718 alloy are studied in detail. On the one hand, slower laser scan speeds and higher angles of inclination in laser welding can lead to an unstable keyhole configuration, which typically results in porosity. On the other hand, faster scan speeds result in longer melt pools, and Rayleigh instabilities can cause the elongated melt pool to break down into tiny islands of molten metal resulting in balling defects. Additionally, effects of powder packing density, laser power and particle size distribution on the formation of balling defects are explored. It is also seen that recoil pressure and material evaporation play important roles in determining the melt pool dynamics and surface morphology. Finally, melt pool data from the numerical models is used to study and predict the solidification morphology for the IN718 alloy. Based on temperature gradients and solidification rates, which can be obtained through CFD models, it is possible to determine the resulting microstructure evolution and primary dendrite arm spacing resulting from the powder bed fusion processes. These results are compared to experimental data wherever available.

These high fidelity, multiphysics CFD models provide a framework to better understand AM processes from the particle and melt pool scales. Using this information, it will be possible to more accurately model additional aspects of AM processes such as thermal and residual stresses and distortions in the entire part build.

### *1.1. CASE STUDY 1: Effects of random powder distribution and material evaporation on melt pool dynamics<sup>1</sup>*

A three-dimensional numerical model that incorporates a randomly-distributed powder bed and material evaporation is developed using FLOW-3D to investigate melt pool dynamics with keyhole formation by an Nd-YAG laser. The discrete element method (DEM) was employed to simulate powder packing, which accounts for the motion of a large number of particles including particle/particle and particle/wall interactions. The model was validated by measuring the particle size distributions in specific areas and ensuring that no powder size segregation occurs. Next the flow behaviour of the melt pool is characterized by calibrating parameters in the numerical model to achieve good agreement with the experimental results. The importance of including material evaporation in the numerical model is demonstrated by measuring the melt pool dimensions, which turn out to be narrower and deeper than when evaporation effects are not considered. Moreover, a keyholing effect is observed due to the recoil pressure resulting from evaporation, which affects surface morphology and surface temperatures of the melt pool. As illustrated in Figure 1, the contours of the cross-sections of the melt region including the dimensions and surface morphology compare very well between the simulations and experiments, justifying the importance of including evaporation effects.

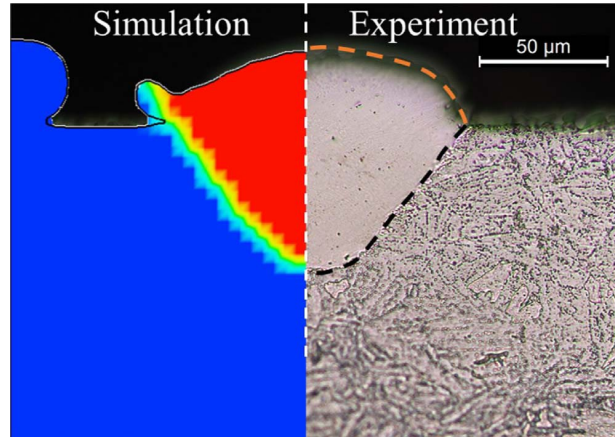


Fig. 1. Validation of the melt-pool dimensions (black-dashed line) and the surface morphology (orange-dashed line).

## 1.2. CASE STUDY 2: Simulation of Heat Transfer and Fluid Flow in Laser Powder Bed Additive Manufacturing<sup>2</sup>

Process parameters such as laser scan speed, laser power, packing density and particle size distribution have a direct effect on melt pool dynamics in a laser powder bed fusion process. The highly transient nature of the melt pool affects the final surface quality of the solidified melt region.

As illustrated in Figure 2, balling defects occur when the molten pool becomes discontinuous and breaks into separated islands of molten metal. Such defects can be attributed to void formations in the melt pool, which eventually break the melt pool into separate regions as seen in Figures 2(c) – 2(d). Strong backward flow because of surface tension gradients is usually the driving force behind the formation of these voids.

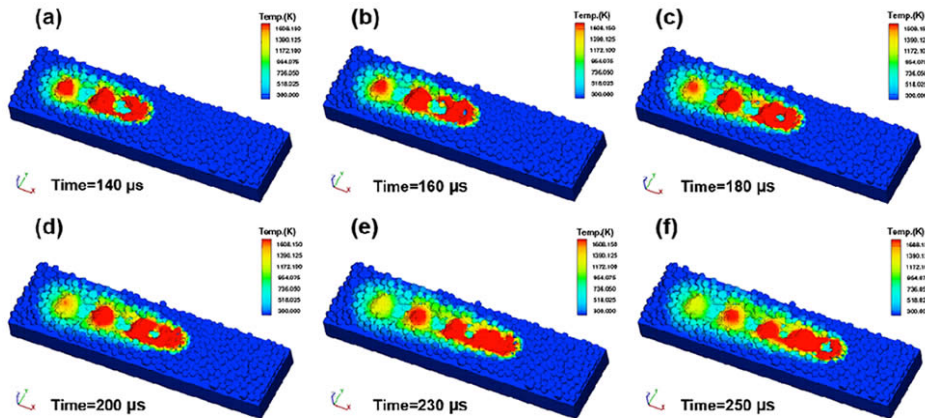


Fig. 2 (a)-(f). Validation of the melt-pool dimensions (black-dashed line) and the surface morphology (orange-dashed line).

Additionally, it is found that the high scanning speeds and a particle size distribution which is skewed to a higher number of larger sized particles are detrimental to the surface quality and can potentially cause balling defects. However, using a higher powder packing density can potentially reduce the onset of balling

defects. This paper summarizes the effects of several process parameters on melt pool dynamics and formation of balling defects for L-PBF processes in Inconel® 718.

### 1.3. CASE STUDY 3: Modelling of heat transfer, fluid flow and solidification microstructure of nickel-base superalloy fabricated by laser powder bed fusion<sup>3</sup>

The microstructure evolution in laser powder bed fusion processes is investigated using fluid flow and heat transfer models built in **FLOW-3D**. Solidification parameters, particularly solidification rate and temperature gradients that are calculated from temperature fields are used to assess solidification morphology and grain size for L-PBF of Inconel® 718 using existing theoretical models. The numerical models are validated by calibrating the dimensions of the melt pool for two partially overlapping laser scan tracks, and it can be seen below in Figure 3 that the cross-sectional dimensions compare well between experiments and simulations.

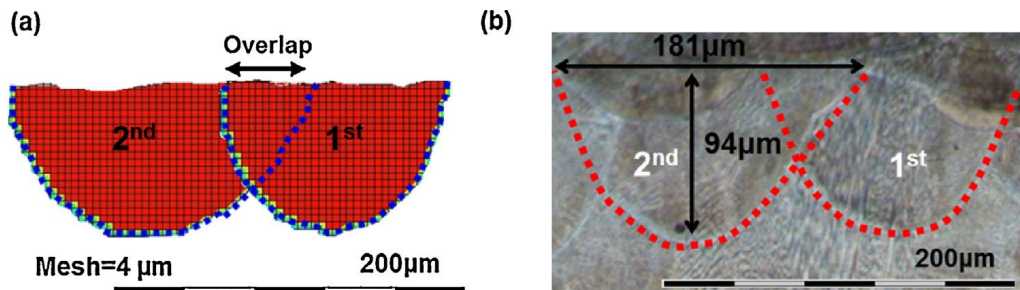


Fig. 3. Comparison of (a) calculated and (b) experimentally measured molten pool shapes.

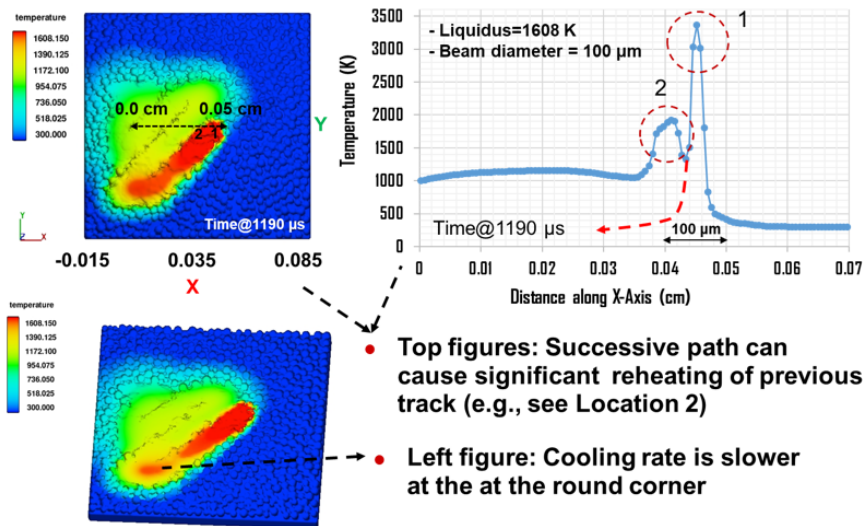


Fig. 4. Temperature gradients are extracted from simulation results to compute microstructure data.

Figure 4 shows the theoretical scanning pattern used in the simulation. Solidification parameters at the molten pool side edge and the molten pool trailing end are calculated. These locations correspond to the maximums and minimums of solidification parameters, and by using existing analytical models for welding and cladding processes, it is calculated that columnar dendrite is the dominant morphology in IN718 made by L-PBF. The primary dendrite arm spacing (PDAS) is another important microstructure parameter and the dendrite size was estimated to be between 1.32 and 1.87  $\mu\text{m}$ . The calculated solidification morphology and PDAS are consistent with experimentally observed results. The reader is invited to refer to the cited journal article for more information on the methodology and results.

#### 1.4. CASE STUDY 4: Multi-physics modelling of single/multiple-track defect mechanisms in electron beam selective melting<sup>4</sup>

A high-fidelity powder scale and fluid flow model is built in **FLOW-3D** to investigate detailed formation processes of single/multiple-track defects, such as balling, inter-track void formation and single-track non-uniformity in a selective electron beam melting process. The computation models reveal the influence of process parameters such as scan patterns, laser powers and hatch spacing on the subsequent quality of the melt pool as seen in Figure 5 below.

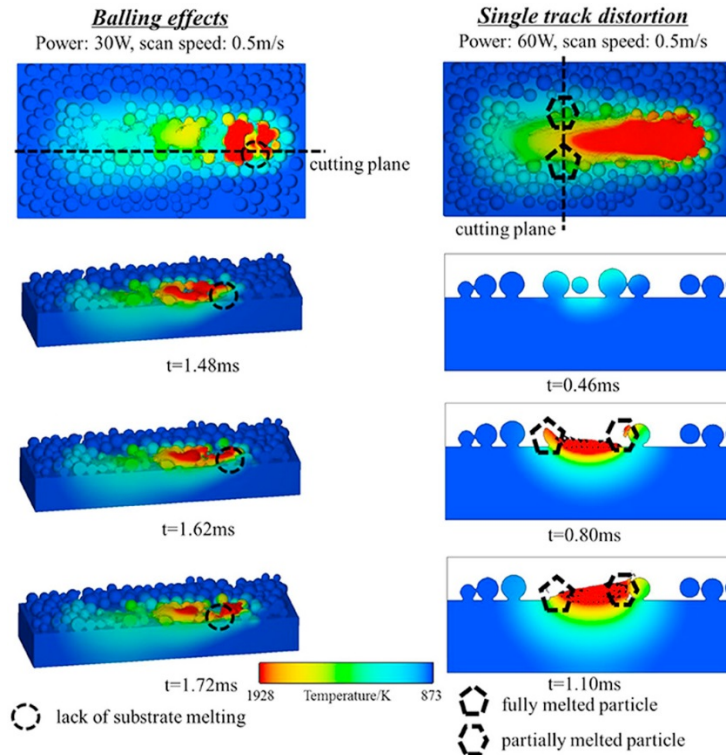


Fig. 5. Simulation results of balling defects and single-track distortions.

Several scan patterns, including unidirectional scans, counter-directional scans, layer-wise rotated and inter-laced scan strategies are analysed in detail to investigate their effects on formation of voids. It is found

that the hatch spacing must be no larger than the width of melted region within the substrate and that the inter-laced scan strategies result in the least void formation among all the scan strategies implemented.

## **References**

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