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MODELLING HEAT TRANSFER IN POWDER BED ADDITIVE MANUFACTURING

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ABSTRACT

One of the most important ingredients in a numerical model of Additive Manufacturing (AM) is a heat transfer model. On its own this is challenging enough as conductive, convective and radiative heat transfer mechanisms are all important, coupled with liquid/solid phase changes. For metals and alloys the process is also inherently multiscale – a perennial problem in materials science. Furthermore, heat transfer is only the first step to predict different phenomena of interest including metallurgical microstructure, defects and thermal stresses to name a few. This paper briefly touches on several of these areas, all of which merit concerted effort by the modelling community.

Key Words: *Heat Transfer, Powder Bed Fusion, Additive Manufacturing.*

1. INTRODUCTION

For metals both conventional casting and AM processes involve melting and solidification. They share some problems (e.g. porosity, thermal stress, multiscale) but AM brings a new set of problems (e.g. vaporization/keyholing, spatter, much smaller scale fluid flow, powder shape/size distribution or PSD effects). Furthermore, the technology of AM machines is constantly changing; probably more so than casting on top of which specific new alloys for AM will inevitably emerge. Commercial AM codes are still under development. As is the case for casting there is always a play off between accuracy and industrial usefulness. Heat transfer modelling is a key ingredient in these models for prediction of quantities of interest.

2. KEY PHENOMENA IN BRIEF

The principal heat transfer effects in AM include conductive (within the melt pool and into the surrounding powder) convective (within the melt pool but also protective gas flows over the bed) and radiative (laser heating of the powder and radiation effects within the powder [1]). Use of incorrect machine settings for laser speed and/or laser power can lead to ‘keyholing’ and vaporization and spatter or alternatively insufficient melting (Figure 1) [2]. PSD effects, granular flow of powders (Figure 2), thermal stresses and distortion all conspire together to complicate the process further [3-5]. Some representative results are shown below based on Powder Bed Fusion (PBF) of metallic powders using Renishaw AM250, AM400 and AM500 machines.

3. SOME RESULTS

Modelling at the powder level can provide fine scale predictions of melting and solidification [3, 6]. Results from such models can then provide a basis for meso structural modelling (i.e. grains) [7]. Experimentation to validate such models can be provided by experiment e.g. a recent crucible experiment design [8] where several crucibles are built, varying powder depth and laser

speed/power (Figure 3), to construct process maps and investigate melting/defect effects (Figures 4 and 5).

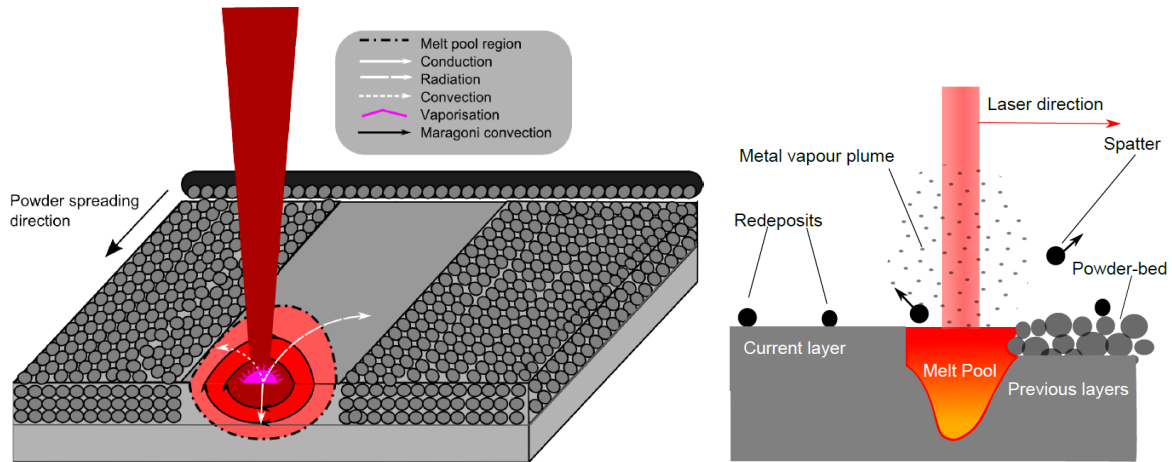


FIGURE 1. Schematic showing Left) physical phenomena inherent within the laser powder bed fusion process and Right) the potential by-products in the PBF process [2].

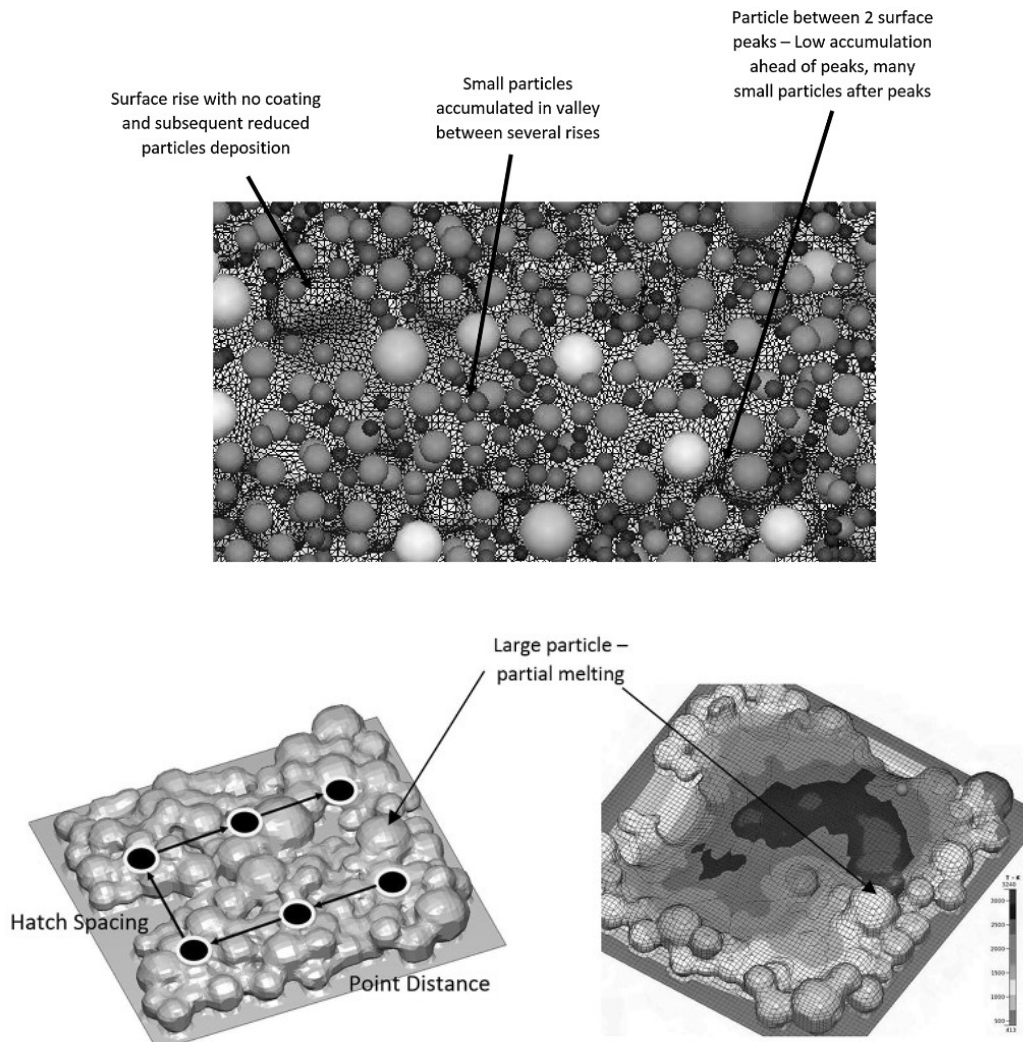


FIGURE 2. Top) Powder layer spread on previously processed surface, Bottom left) laser hatch pattern processing strategy, Bottom right) final surface shape after processing [3].

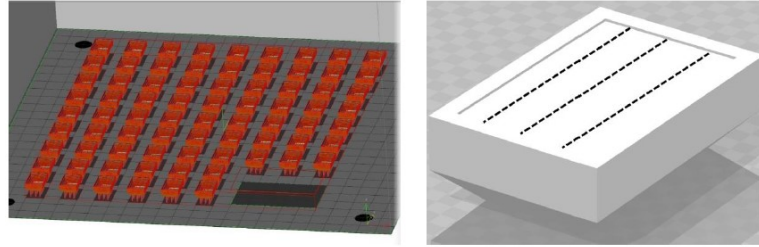


FIGURE 3. Left) CAD drawing of crucibles on base plate used during an experiment, Right) Three single track structures placed at the top of the crucibles [8].

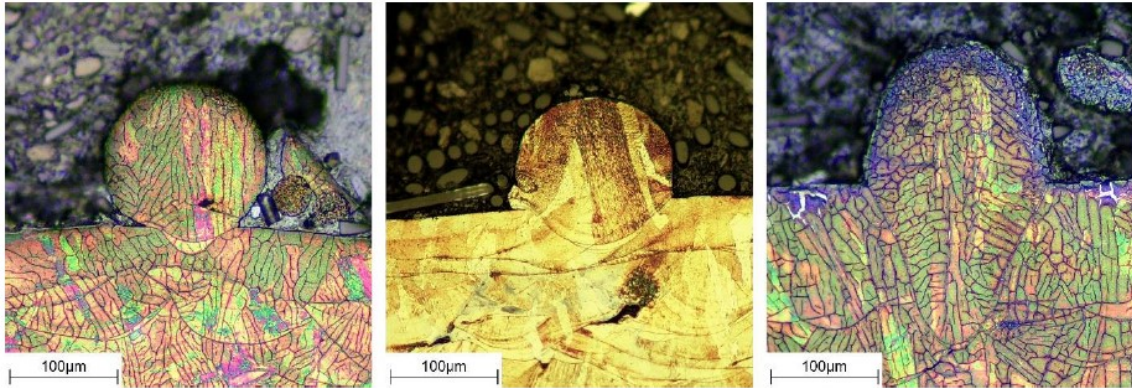


FIGURE 4. Representative results for stainless steel (SS316L) - The three types of tracks formed for laser powers and speeds of Left) insufficient melting 200W , 700mm^{-1} , Middle) optimal conduction mode 150W , 300mm^{-1} , Right) keyholing 175W , 200mm^{-1} [8].

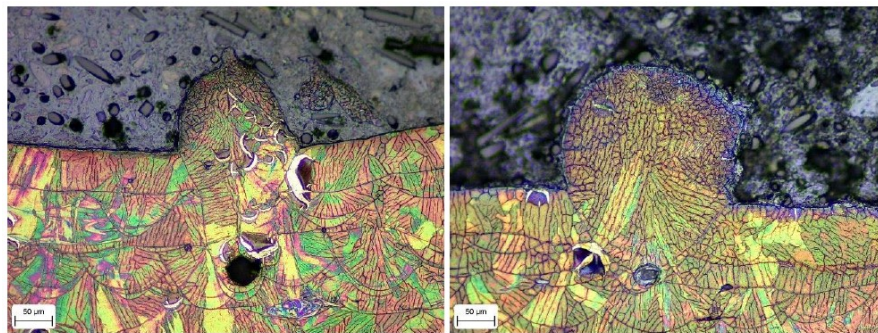


FIGURE 5. (SS316L) – Typical keyhole porosity observed for stainless steel (SS316L) for laser powers and speeds of Left) 200W , 300mm^{-1} , Right) 175W , 100mm^{-1} [8].

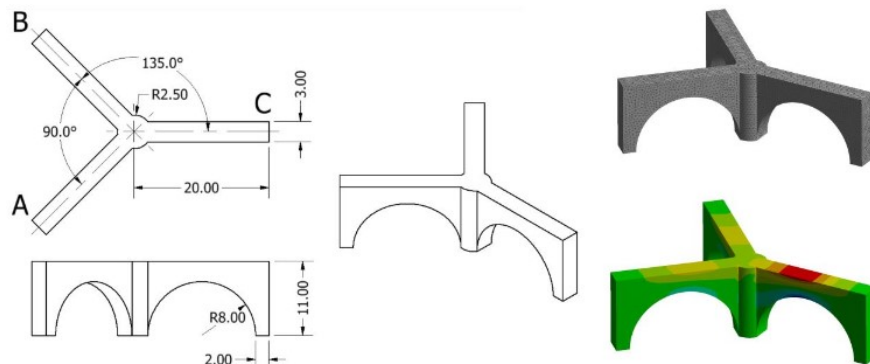


FIGURE 6. Three Prong Method Component Dimensions, Mesh and Stress Analysis [10].

The likelihood of insufficient melting, optimal (conduction mode) melting and unwanted high penetration (keyhole) melting can be determined (Figure 4 left, middle, right respectively). Certain defects (e.g. porosity associated with keyholing) can also be identified (Figure 5) along with grain structures for meso scale grain model validation. However, powder scale models are less useful when dealing with component scale problems such as thermal stress. Simplified macro models are more likely to be useful which exploit continuum approximations to the powder bed [e.g. 2, 9]. Experimental measurement of thermal stresses arising in PBF is also a work in progress for researchers in this field (e.g. Figure 6) [10].

Finally, and returning to the very first sentence, the modelling of casting processes has evolved over several decades [e.g. 11] and yet still engages many researchers in further development. Modelling of AM processes has benefited from this related body of work but is yet to reach the same level of commercial applicability. A predictive capability for microstructure/defect evolution, macro scale thermal stress phenomena, all packaged into a closed-loop control system for AM machines to ensure process optimization and reproducibility, is the ultimate goal [12].

4. CONCLUSIONS

There are significant opportunities for the development of new models for additively manufactured components. These components exhibit very different structures from conventionally cast materials and the side-effects of laser processing are many and varied. Numerical models to link processing parameters to material performance are at a fairly early stage of development and are highly dependent on sound thermal models. Realization of such models would significantly enhance future innovation in this rapidly developing field and as such represent a rich field of study for modellers.

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