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MULTI-PHYSICS NUMERICAL MODELLING OF 316L AUSTENITIC STAINLESS STEEL IN LASER POWDER BED FUSION PROCESS AT MESO-SCALE

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ABSTRACT

Laser Powder Bed Fusion (L-PBF) is a Metal Additive Manufacturing (MAM) technology where a complex 3D metal part is built from powder layers, which are selectively consolidated using a laser heat source. The processing zone is in the order of a few tenths of micrometer, making L-PBF a multi-scale manufacturing process. The formation and growth of gas pores and the creation of un-melted powder zones can be predicted by multiphysics models. Also, with these models, the melt pool shape and size, temperature distribution, melt pool fluid flow and its microstructural features like grain size and morphology can be calculated. In this work, a high fidelity multi-physics meso-scale numerical model is developed for stainless steel 316-L which includes melting, solidification, fluid flow, surface tension, thermo-capillarity, evaporation and multiple reflection with ray-tracing. A statistical study using a full Design of Experiments (DoE) method was conducted, wherein the impact of uncertain material properties and process parameters namely absorptivity, recoil pressure (vaporization) and laser beam size on the melt pool shape and size was analysed. Furthermore, to emphasize on the significance of the above mentioned uncertain input parameters on the melt pool dynamics, a main effects plot was created which showed that absorptivity had the highest impact followed by laser beam size. The significance of recoil pressure on the melt pool size increases with melt pool volume which is dependent on absorptivity. The prediction accuracy of the model is validated by comparing the melt pool shape and size from the simulation with single track experiments that were produced with similar process parameters. Moreover, the effect of thermal lensing was considered in the numerical model by increasing the laser beam size and later on the resultant melt pool profile was compared with experiments to show the robustness of the model.

1. INTRODUCTION

L-PBF is a MAM process where a powder layer with a defined thickness is deposited on a built plate and later on a laser beam selectively melts different regions of the powder bed according to the sliced 3D CAD geometry. The process of powder deposition and selective laser melting is repeated through a layer-by-layer method until a complete 3D part is produced. LPBF offers advantages like mass customization, high design freedom and reduction in material waste, thus L-PBF has succeeded to attracted interest from aerospace, automotive and medical industries. However, parts produced by L-PBF suffers from defects such as gas pores, voids, delamination, thermally induced residual stress and deformations. To control these defects, either in-situ online monitoring or ex-situ inspections are required especially for automotive and aerospace applications where the level of safety standards are high. However due to the micron size processing zone and the multi-physics involved, the online monitoring of the process is physically limited, expensive and needs calibration. Ex-situ inspection methods based on trial-and-error experiments are time-consuming and create material waste. Hence, high fidelity numerical models can be very useful to predict important information like melt pool temperature, melt pool size and defects created during the laser melting process. Also, the optical elements are exposed to the high laser temperatures during the L-PBF process that can lead to laser defocusing on the powder bed surface, which is caused by the high sensitivity of refractive index towards thermal gradients on the surface of the optical components [1,2]. Thermal lensing and laser energy attenuation by laser-spatter interaction adds an uncertainty to the laser beam diameter and optical

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absorptivity respectively. Also at high laser energies, there is an uncertainty in calculating the local temperature of atmospheric gas near the laser-material interaction zone due to the presence of the vapour plume [3]. This leads to an uncertainty in the magnitude of recoil pressure present on the melt pool surface which is formed due to the evaporation phenomenon.

In this work, a high fidelity numerical model of the L-PBF process for 316L stainless steel is developed wherein the effect of uncertain model input parameters including the laser beam diameter, absorptivity and recoil pressure on the melt pool size was analysed by using a DoE method. The shape and size of the predicted melt pools are analysed and are both qualitatively and quantitatively compared with experiments for validation.

2. NUMERICAL MODEL AND EXPERIMENTS

The Finite Volume Method (FVM) is used for discretizing the heat transfer and Naiver-stokes equations as well as modelling the thermal and fluid dynamics conditions of the melt pool and the model is developed in the commercial software Flow-3D. The Volume of Fluid (VOF) algorithm is implemented to capture the free surface of the molten fluid. A Gaussian laser heat source was incorporated into the model using a multiple reflection ray tracing method which is much more realistic compared to an idealized volumetric heat source [4]. Keyhole melting modes can be accurately captured by the ray tracing method and defects like keyhole-induced gas porosities can be predicted by the model as well. Prior to the Computational Fluid Dynamics (CFD) simulation, a Discrete Element Method (DEM) was used to deposit a layer of spherical powder particles on a substrate with a similar powder particle size distribution to the experiments. A 'rainfall' method is used to deposit the powder layer. Later, the powder particles are imported into the CFD model along with a substrate. A Newtonian viscous non-compressible fluid with a laminar fluid flow, a linear solidification model with enthalpy-porosity method and the immobility of powder particles during the melting process were some of the assumptions made in the model. For more details about the governing equation used in the model, the reader is referred to the previous work of the author group [5,6].

The dimensions of the overall computational domain are 1100 x 500 x 350 µm, which includes a powder layer and a substrate as shown in Figure 1 (a) and the process parameters used in the single-track experiment are 80 W laser power, 500 mm.s^{-1} scanning speed and 15 µm beam radius. The computational domain was discretised with a global cell size of 5 µm after conducting a mesh convergence test. The discretized computational domain and the melt pool morphology at two locations along the scanning direction 'x' are shown in Figure 1, where at x = 550 µm the melt pool achieves its pseudo-steady state as shown in Figure 1.

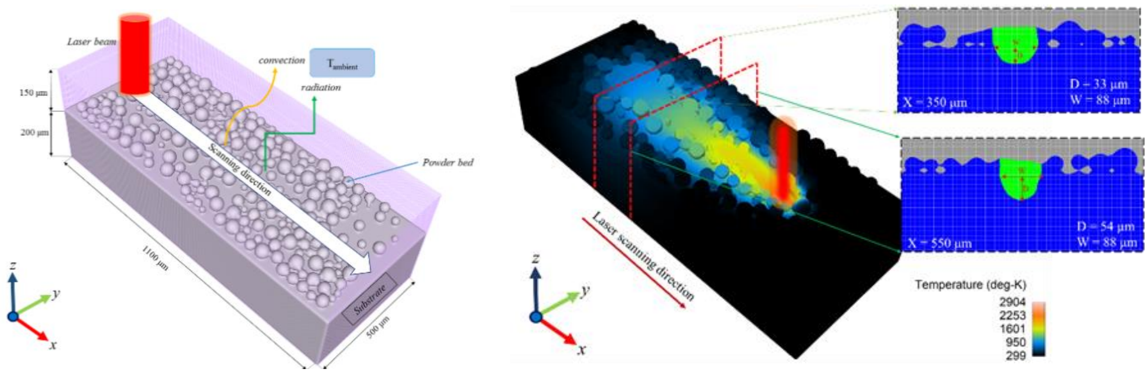

Figure 1: a) Computational domain for single track L-PBF which includes a 200 µm thick substrate and 45 µm powder layer thickness b) 3D temperature contour plot after scanning a single track with melt pool contours at two locations along the scanning direction where the green region indicates the melted regions.

The effects of uncertain model input parameters including laser beam spot size, absorptivity and recoil pressure due to thermal lensing, particle spattering and material vaporization phenomena could be analysed by conducting a parametric investigation based on a full factorial DoE method. In the DoE framework, three values of each uncertain parameter were selected as shown in

Table and a set of simulation cases were run. The resultant melt pool dimensions were compared to the experiments at a location where the melt pool attained a pseudo-steady state. The melt pool depth and width are the two dimensions which are considered when validating the numerical model.

Table 1: Three levels of three input model parameters with high uncertainty used in the DoE

Parameter	Low level	Mid-level	High level
Laser beam radius (μm)	12	15	18
Absorptivity (-)	0.1	0.25	0.45
Recoil pressure coefficient B (-)	1	10	20

3. RESULTS AND DISCUSSION

The full factorial DoE has 27 simulation cases, which were solved, and the error in the simulated melt pool dimensions with respect to the experimental values were calculated. A low error % in the melt pool size was predicted in cases where an absorptivity of 0.45 was used irrespective of the laser beam radius and recoil pressure coefficient defined in Table 1. This shows that the laser absorptivity has the strongest influence on the melt pool size and molten volume. To visualize the influence of the three input parameters on the melt pool dimensions, a main effects plot is shown in Figure 2.

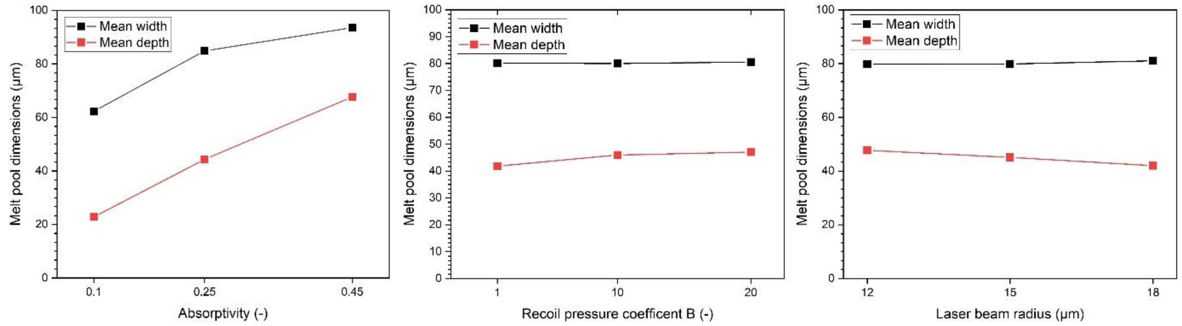

Figure 2: Main effects plot of uncertain parameters: absorptivity, recoil pressure coefficient and laser beam radius on the melt pool dimensions (width and depth)

The numerical model predicts that with an increase in laser absorptivity, there is an increase in melt pool dimensions as higher thermal energy from the laser radiation is absorbed by the powder layer and substrate. The influence of the laser absorptivity on the melt pools' size and shape is also clear when comparing Figure 3 (a) and (d) wherein absorptivity of 0.1 and 0.45 was used respectively. In Figure 2 (a) with an increase in absorptivity from 0.25 to 0.45, a sharper increase in the melt pool depth than the melt pool width is observed due to stronger activity of Marangoni convection and recoil pressure. The increase in the magnitude of the Marangoni convection and recoil pressure leads to an increase in melt pool width and depth, respectively. Moreover, this shows that the recoil pressure, Marangoni convection and surface tension are the main driving forces of the melt pool dynamics.

The increase in recoil pressure has a significant effect on the melt pool depth but is insignificant on the width as shown in Figure 2 (b) and the same is noticed when comparing the 3D temperature contours in Figure 3 (d) and (e) where absorptivity is 0.45 and laser beam size is 12 µm in both the cases. Thus by increasing the recoil pressure, a deep and narrow laser drilling effect which increases the melt pool depth. However, when the recoil pressure coefficient is increased from 1 to 20 at an absorptivity value of 0.1, the increase in melt pool depth is insignificant as shown in Figure 3 (a) and (b). Thus the impact of recoil pressure on the melt pool depth depends on the value of absorptivity and is more impactful at higher absorptivity values.

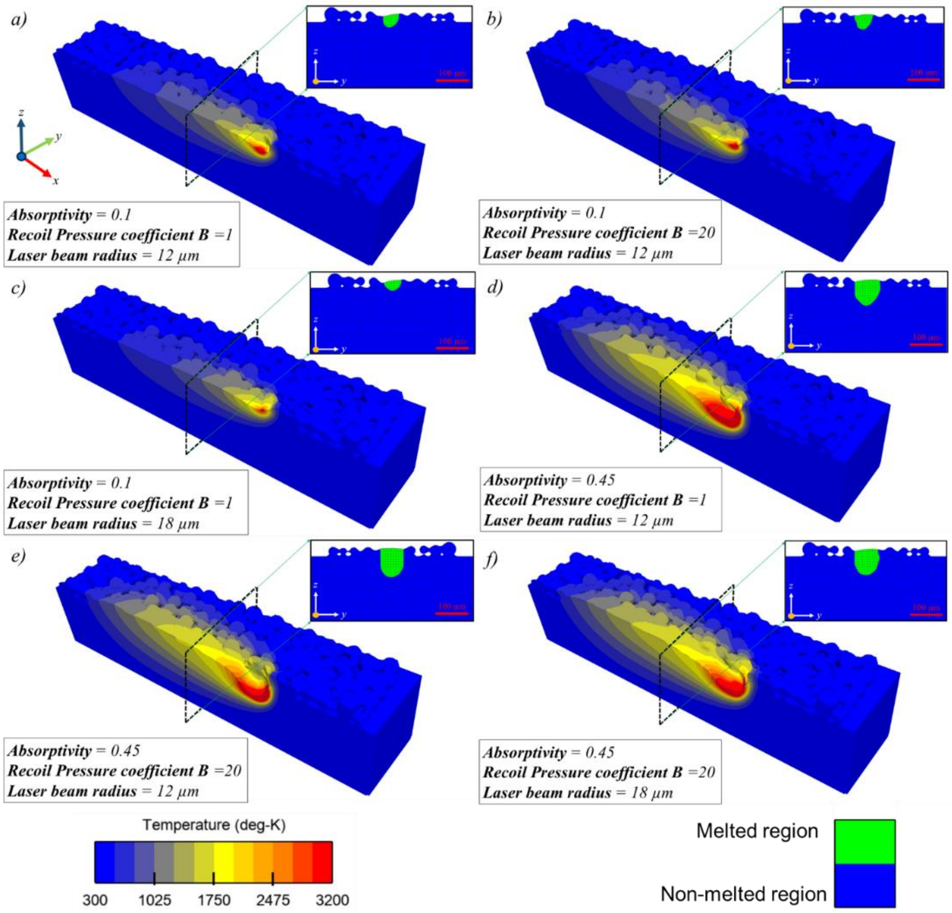

Figure 3: 3D temperature contours and 2D melt pool cross-sections where the melt pool is stabilized at x=500 µm from the start of the laser initial location for cases where (a) absorptivity = 0.1, Recoil pressure coefficient B = 1 and laser beam radius = 12 µm, (b) absorptivity = 0.1, Recoil pressure coefficient B = 20 and laser beam radius = 12 µm, (c) absorptivity = 0.1, Recoil pressure coefficient B = 1 and laser beam radius = 18 µm, (d) absorptivity = 0.45, Recoil pressure coefficient B = 1 and laser beam radius = 18 µm, (e) absorptivity = 0.45, Recoil pressure coefficient B = 20 and laser beam radius = 12 µm, (f) absorptivity = 0.45, Recoil pressure coefficient B = 20 and laser beam radius = 18 µm.

As explained earlier, thermal lensing phenomenon causes an uncertainty to the laser spot size and the resulting impact of such laser spot size variation on the melt pool dimensions is shown in Figure 2 (c) wherein an increase in the laser beam spot size decreases the melt pool depth and widens the melt pool. Larger laser beam sizes irradiate a bigger powder bed surface area causing a wider distribution of the laser heat flux followed by reduction in the peak intensity at the center of the laser beam. This results in reduction of melt pool depth and increase of width as shown in Figure 3 (e) and (f). In some L-PBF works, printing strategies including change in laser beam size are used as an additional process parameter, where an increase in the laser beam size increases the melt pool width while a decrease in laser beam size increases the depth [7]. From the DoE results, it is elucidated that the laser absorptivity is the most influential process parameter on the melt pool dynamics and the significance of recoil pressure on the melt pool dynamics depends on the value of absorptivity.

After analysing the effects of the uncertain parameters on the melt pool size and shape, the simulation case from the DoE which predicted a minimum error in melt pool depth and width is chosen for further examination. More specifically, it is compared with the first single laser track from experiments (minimum thermal lensing effect) as shown in Figure 4 (a). The numerical model accurately predicts the melt pool size and shape when thermal lensing is ignored in the model. The same values of recoil pressure coefficient and absorptivity were used in a new simulation model with a laser beam radius of 20 µm to passively incorporate the effect of laser beam defocusing caused by thermal lensing as shown in Figure 4 (b). The focal plane shift reduces the melt pool depth and increases the melt pool width which is evident in the experiments and the simulation results comparing Figure 4 (a) and (b).

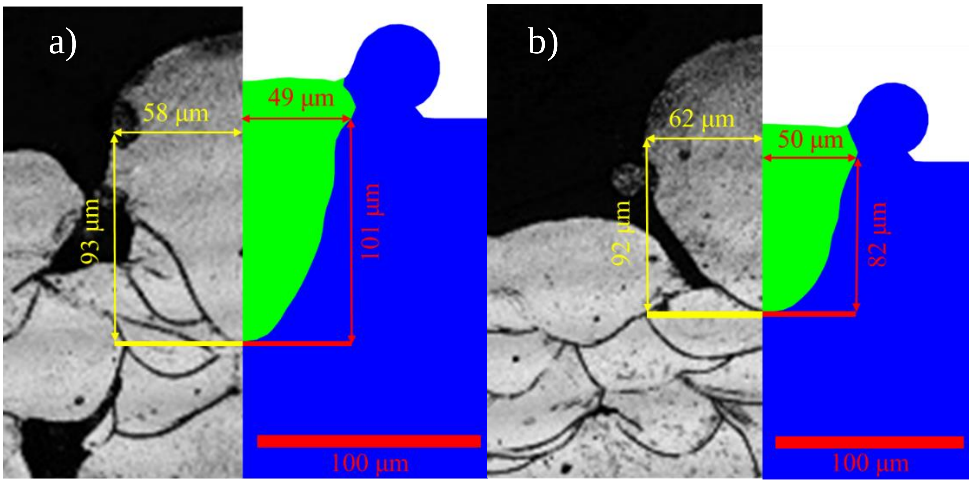

Figure 4: Validation of Numerical model with Recoil pressure coefficient B= 20, absorptivity = 0.45 and a) laser beam radius = 15 µm b) laser beam radius = 20 µm

4. CONCLUSION

In this work, a high-fidelity multi-physics numerical model was developed for L-PBF using the FVM method in Flow-3D. The impact of uncertainty in the input parameters including absorptivity, recoil pressure and laser beam size on the melt pool is addressed using a DoE method. The DoE analysis shows that absorptivity has the highest impact on the melt pool. The recoil pressure and laser beam size only become significant once absorptivity is 0.45. Furthermore, the numerical model is validated by comparing the predicted melt pool shape and size with experiments conducted with similar process parameters wherein a high prediction accuracy is achieved by the model. In addition, the impact of thermal lensing on the melt pool dimensions by increasing the laser beam spot size is considered in the validated numerical model and the resultant melt pool is compared with experiments.

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