Materials and Design 156 (2018) 143–153

Contents lists available at ScienceDirect

Materials and Design

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

Selective laser melting finite element modeling: Validation with high-speed imaging and lack of fusion defects prediction

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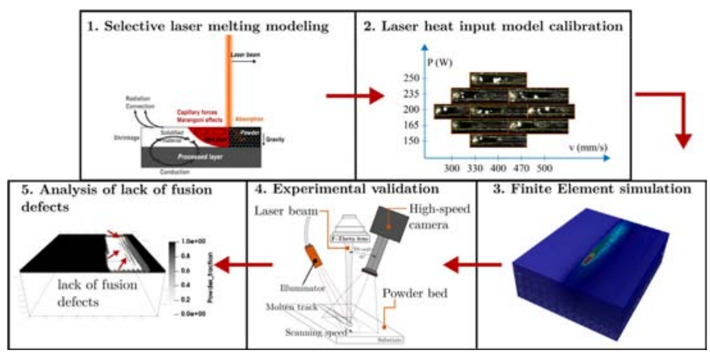
HIGHLIGHTS

- SLM process simulation development, calibration, and validation are presented.
- A thermal FE model was implemented to predict phase transformations.
- A heat source was calibrated using high-speed imaging and metallographic analysis.
- Process validation was carried out using real time high-speed images of the melt pool.
- Simulations of multiple track scans were used to analyze lack-of-fusion formation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 April 2018
Received in revised form 11 June 2018
Accepted 20 June 2018
Available online 22 June 2018

Keywords:
Selective laser melting
Finite element modeling
High-speed imaging

ABSTRACT

Selective laser melting (SLM) is a fast-growing technology which still lacks knowledge and management for wider industrial use. Numerical modeling is today a standard tool in the manufacturing industry to support design and process parameters determination. It is thus of great importance to experimentally validate the simulations in order to ensure their predictive capabilities. However, the fast nature of the process complicates observation of the quantities required for the simulation validation. A finite element model (FEM) of the SLM process is proposed here, together with its numerical validation by comparison with the literature, and experimental validation using high-speed imaging. The melt pool widths and lengths retrieved from the simulation and the videos were measured. The model demonstrated a good accordance with both the literature and the experimental results. Reduced melt pool geometries were simulated in the first tracks which led to lack of fusion defect formations.

1. Introduction

Selective laser melting (SLM) is one of the layer-based additive manufacturing processes. Using this technique, functional parts can be built layer by layer to obtain a final 3D geometry that could not be reached by traditional manufacturing processes. Moreover, the highly concentrated heat input provided by the laser enlarges the range of processable materials to include metal [1]. The extended variety of manufacturable geometry and materials make this technology particularly suitable for fields such as the biomedical industry and aeronautics [2]. However, the process still relies on trial-and-error learning and SLM produced parts are still quite often not qualified, which limits the industrial development of this technology [3]. A first way to gather knowledge about a process is to use empirical methods such as design of experiment [4]. However, experimental characterization of a process may become time and resource consuming, and empirical modeling is often restrained to

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https://doi.org/10.1016/j.matdes.2018.06.037

the application it was developed for and is hardly expandable [5]. In a common approach, simple geometries are produced with variable process parameters and part density is measured. Such an approach is effective, though is limited to being extended to smaller features or bulky components. Moreover, other defects such as thermal distortions require an estimation of the thermal gradients generated during the process. Gaining a better insight of the process through a reliable and realistic physical model can offer a good alternative [6]. One key challenge is then to ensure that the model generates sufficiently accurate results in a limited amount of time, not exceeding the experimentation cost. Despite various attempts to simulate the process (as reviewed by [7], or more recently [8-10] for example), experimental validation of SLM models is indeed still an open issue that has been sparingly discussed in the recent literature. Many models have been validated employing post-experiment melt pool measurement by observing the metallographic cross-sections of the produced samples [11-13]. The major advantage of this technique is its practical simplicity and availability. It has however two major drawbacks: first it is not an on-line measurement, and second it is destructive. To address those issues Denlinger et al. [14] developed a thermocouple setup. Nevertheless, due to the limitations in terms of maximal measurable temperature and response time of said device, the measurements are performed away from the molten pool which is the most critical area. Cheng et al. [15] developed a setup for electron beam melting using a near infrared thermal camera. The major advantage of this method is the possibility to register on-line melt pool temperatures. However, the reliability of the measurements is strongly related to a complex calibration procedure and the temporal resolution of said device (60 Hz) is limited which does not allow all the melt pool dynamics, which contain very fast phenomena, to be caught. High-speed imaging (HSI) can address this issue since it allows to take up to hundreds of thousands of images per second. Previous use of this technology for model validation purposes is reported in [16] and [17]. Riedlbauer et al. used HSI to monitor the presence of molten material but no quantitative measurements of the melt pool were taken on the recorded images. On the second article, Scipioni et al. used the high-speed videos, recorded with a camera mounted coaxially with the laser beam, to estimate the cooling rates and measure the melt pool length on a reduced area of single-track experiments. Evidently, literature lacks a direct on-line comparison between observed and simulated melt pool geometries. A finite element model (FEM) is proposed here, together with its numerical validation against the literature [18,19] and its experimental validation using HSI. A full single-layer multi-track experiment was recorded with a fixed high-speed camera and the corresponding simulation was run for comparison. To the authors' knowledge, no previous work has attempted to provide a full framework of process modeling that involves all steps from model development, to its experimental calibration and its validation with in-situ melt pool geometry measurements.

The paper presents a complete strategy dedicated to the development of an SLM finite element model. First, an in-house thermal FEM able to compute the melt pool geometry and related levels of fusion at millimeter-scale is introduced. An original method to experimentally calibrate the heat input developed to improve the accuracy of the simulations follows. Then, the paper introduces a direct measurement of in-situ molten pool geometries on a single-layer multi-track experiment. To monitor the fast and reduced-size melt pool dimensions, high-speed video recording was used together with a dedicated method to extract the width and length from the images obtained. A comparison between the simulated and the experimentally measured molten pool dimensions follows for validation purposes. Finally, the analysis of the predicted levels of fusion reveal and explain one mechanism of lack of fusion defect appearance and make it possible to demonstrate how the model can be of value in a process parameter optimization procedure.

2. Material and method

The workflow, illustrated Fig. 1, follows a standard and consolidated approach in process simulation, which appears to have been neglected in the case of SLM. Previous works of our group have identified the model, applied the heat source calibration and implemented the solver. The following summarizes these phases, concentrating on the final simulation and validation aspects.

2.1. Finite element model

The model under study is an FEM that was developed in-house and implemented using the deal.ii library [20]. A comprehensive description of the model can be found elsewhere [21] and its main features will be recalled here.

2.1.1. Mathematical formulation

The current model aims at simulating layer-based selective laser melting of metals at mm-scale. Among the main features that must be considered in the SLM simulation are:

- A moving heat source with a prescribed trajectory
- Convective cooling and radiation between the free surfaces of the part and the building chamber atmosphere
- Description of the phase changes solid liquid and powder → consolidated material
- Temperature- and phase-dependent material properties

The main simplifying assumptions are the following:

- The melt pool fluid dynamic is not included
- The powder is considered as a homogeneous material

The assumptions are standard considering the geometrical scale modeled (see for example [22]). They were adopted to limit the computational load to tractable levels. The characteristics translate into the following partial differential equation system:

$$\begin{cases} c_p(T)\rho(T)\frac{\partial T(\mathbf{x},t)}{\partial t} - \nabla\cdot k(T)\nabla T(\mathbf{x},t) = f(\mathbf{x},t) & \text{on} \quad \Omega, t>0 \\ T(\mathbf{x},t) = T_{\mathrm{amb}} & \text{on} \quad \Omega, t=0 \\ T(\mathbf{x},t) = T_{\mathrm{amb}} & \text{on} \quad \Gamma_D, t>0 \\ k(T)\,\frac{\partial T(\mathbf{x},t)}{\partial n} = \alpha(T) & \text{on} \quad \Gamma_R, t>0 \\ k(T)\,\frac{\partial T(\mathbf{x},t)}{\partial n} = 0 & \text{on} \quad \Gamma_N, t>0 \end{cases} \tag{1}$$

with:

$$\rho = \rho(T,\Phi),\ c_p = c_p(T,\Phi),\ k = k(T,\Phi),\ \alpha(T) = \sigma\varepsilon T^4 - T_{\mathrm{amb}}^4 + h(T - T_{\mathrm{amb}})$$

where:

T is the temperature (K), Φ is the fraction of powder/consolidated (solid or liquid) material, ρ is the density (kg m^{-3}), k is the thermal conductivity (W m^{-1} K^{-1}), c_p is the thermal capacity (J kg^{-1} K^{-1}), T_{amb} is the ambient temperature in the building chamber (K), h is the convection coefficient (W m^{-2} K^{-1}), ε is the material emissivity, σ is the Stefan-Boltzmann constant. Ω is the complete domain, Γ_D is the contact area with the substrate where a fixed temperature (Dirichlet) boundary condition (BC) is applied, Γ_R is the contact area with the environing gas which is where radiation and convection cooling occur (Robin BC), and Γ_N are the lateral faces, embedded in the substrate, that were deemed adiabatic (Neumann BC). An illustration