Materials and Design 113 (2017) 369–376

Contents lists available at ScienceDirect

Materials and Design

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

Two-dimensional simulation of grain structure growth within selective laser melted AA-2024

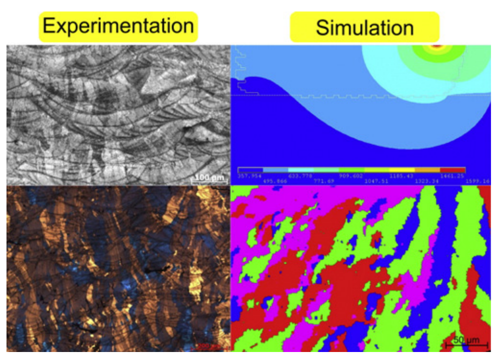
Omar Lopez-Botello [a], Uriel Martinez-Hernandez [b], José Ramírez [c], Christophe Pinna [a], Kamran Mumtaz [a,*]

[a] Department of Mechanical Engineering, University of Sheffield, Sheffield, UK
[b] Department of Automatic Control and Systems Engineering, University of Sheffield, Sheffield, UK
[c] Centro de Investigación e Innovación en Ingeniería Aeronáutica, Facultad de Ingeniería Mecánica y Eléctrica, Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, Mexico

HIGHLIGHTS

- The developed Cellular Automata – Finite Element model accurately predicts the microstructure of components manufactured via Selective Laser Melting.
- The developed Finite Element model accurately predicts the melt pool size in the Selective Laser Melting Process.
- Cooling and solidification rates are calculated with help of the developed Finite Element model.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 August 2016
Received in revised form 3 October 2016
Accepted 14 October 2016
Available online 17 October 2016

Keywords:
Grain structure
Cellular Automata
Finite Element
Selective Laser Melting
Additive Manufacturing

ABSTRACT

A two-dimensional Cellular Automata (CA) – Finite Element (FE) (CA-FE) coupled model has been developed to predict the microstructures formed during the laser melting of a powdered AA-2024 feedstock using the Additive Manufacturing (AM) process Selective Laser Melting (SLM). The presented CA model is coupled with a thermal FE model, which computes the heat flow characteristics of the SLM process. The developed model considers the powder-to-liquid-to-solid transformation, tracks the interaction between several melt pools within a melted track, and several tracks within various layers. It was found that the calculated temperature profiles as well as the simulated microstructures bared close resemblance with SLM fabricated AA-2024 samples. The developed model was capable of predicting melt pool cooling and solidification rates, the type of microstructure obtained, the size of the melt pool (with 14% error) and the heat affected zone, average grain size number (with 12% error) and the growth competition present in microstructures of components manufactured via SLM.

1. Introduction

Selective Laser Melting (SLM) is an Additive Manufacturing (AM) technology that in recent years has experienced notable increases in industrial uptake for the manufacture of end-use engineering components. The SLM technology can be used to process a wide range of metallic alloys (e.g. nickel, titanium, aluminium based etc.). The melting process is rapid, fusing multiple layers successively together creates complex thermal histories within the material. According to Verhaeghe et al. [25] it is crucial to understand the physical phenomena involved within the fabrication process in order to accurately control it.

* Corresponding author.
E-mail address: k.mumtaz@sheffield.ac.uk (K. Mumtaz).

http://dx.doi.org/10.1016/j.matdes.2016.10.031

Numerical methods that simulate the SLM process have been undertaken by several researchers (Shiomi, 1999; [3,6,7,10,12,13,16,18,19,23,26]). Each of these numerical approaches attempts to develop an improved understanding of the physical phenomena that occur during the laser processing of a powder bed (thermal history, Marangoni flows, solidification front, etc.).

Understanding the thermal history of an SLM component has been a main area of investigation. Shiomi et al. [22] developed an FE simulation that calculated the temperature distribution within metallic powders exposed to a pulsed laser and experimentally validated the calculated results. It was found that the maximum temperature reached by the metallic powder was affected by the peak laser power rather than the duration of the laser irradiation. Matsumoto et al. [13] proposed a method to calculate the temperature and stress distribution within a solidified layer within the SLM process using the FE method. Although the effect of a substrate plate was not considered, neither was the detailed thermal dependent properties of the material of interest discussed, it was one of the first research to compute the change from powder-to-liquid-to-solid. Overall, these models are restricted by the complexity of the problem, and the consideration of homogeneous conditions within the model. Roberts et al. [18] developed a three-dimensional FEM model in order to understand the thermal history during layer-by-layer processing, while taking into account the nonlinearities produced by the temperature-dependent material properties and phase changes. Even though their results agree with experiments, it was identified that a more detailed model is needed in order to compute the solidification phenomena within SLM. Loh et al. [12] developed a single layer FEM model using a sacrificial layer (which vaporises) in order to obtain accurate results of the generated temperature profiles within the SLM process, however this approach is not considered as suitable for a multilayer process. Foroozmehr et al. [3] used the optical penetration depth of a laser beam [2] and developed a 3D single layer powder bed model that predicts the temperature profile. Detailed thermal dependent properties (excluding mushy zone properties) were considered, and experimental values were used to calibrate the optical penetration depth. However even though the results are considered accurate, the model does not consider the interaction between layers. In an attempt to predict optimal processing parameters during SLM, Song et al. [23] simulated the process on a three-dimensional FE model and experimentally validated the results, highlighting the importance of a FEM simulation of the SLM process. Numerical models of the SLM process are important in order to achieve a certain degree of control/optimisation of the process [19].

The heat transfer phenomenon within a melt pool formed by the SLM process is highly influenced by the fluid flow [15], solely modelling laser melting process without fluid flow consideration will cause inaccuracies. Khairallah and Anderson [10] demonstrated via a three-dimensional mesoscopic micrometre scale model the importance of including the stochastic nature of the powder bed. Further to this it was found that the physics of the process is driven by the surface tension of the melt pools and subsequently effects heat transfer and topology of the solidified melt pools. Other models such as that developed by Pengpeng and Dongdong [16] used Computational Fluid Dynamics (CFD) to accurately predict the melt pool geometry and temperature distributions present within the process. This work developed a three-dimensional model to simulate the temperature evolution behaviour and the effects of the melt pool dynamics during the SLM process and validated the model with experimental trials. In order to simplify and reduce the simulation processing time, a number of researchers have used the enhanced thermal conductivity approach to account for melt pool convection. Safdar et al. [19] used a proposed enhanced thermal conductivity approach for the SLM process and experimentally validated his results. This investigator states that the enhanced thermal conductivity approach is able to artificially simulate the melt pool convection during the processing of materials in SLM, accurately modelling the melt pool profile and temperature distribution without the need of CFD models.

These studies on thermal behaviour have assisted in improving the understanding of stress formation, melt pool topology and surface tension within the SLM process. The majority of SLM microstructural studies have focussed on observations of experimentally fabricated components. Work undertaken by Yin and Felicelli [26] developed a numerical model of the microstructural development during the LENS laser powder blown process with focus only on a micro region inside the mushy zone of the melt pool. The model developed by Yin and Felicelli [26] does not consider convection on the top surface of the layer, and the obtained results are only relevant for the deposition of a single layer.

Numerical simulation has been used to understand grain growth and develop optimum processing conditions in other metal processing techniques (i.e. casting, forging, etc.) to improve efficiency. Despite the benefits numerical simulation has to offer, the development of an appropriate numerical simulation to model microstructural evolution within powder bed SLM has not yet been reported in literature.

2. Modelling methodology

The purpose of this research is to develop a “first of its kind” microstructural evolution model of the SLM process. The model developed in this work is based on the CA-FE (Cellular Automata-Finite Element) method developed by Gandin and Rappaz [5]. The CA model is generally used to describe the formation of grains during the solidification process, while the FE method is used to calculate the heat flow present within the process. The coupling CA-FE leads to a multiscale model, in which the FE considers the higher scale problem (temperature profiles) and the CA the smaller scale problem (grain growth). The CA-FE technique is used in order to develop a new model which is able to capture the evolution of the microstructural formation during the melting-solidification of various melt pools within several layers of the SLM process.

3. Thermal history modelling

3.1. Governing equations

The SLM process uses a localised laser beam in order to heat and melt the powder bed, as a result heat transfer plays an important role in this process. Generally, the spatial and temporal distribution of the temperature is governed by the heat conduction equation, which can be expressed as:

$$\rho C_p \frac{\partial T}{\partial t} = k_{xx}\frac{\partial^2 T}{dx^2} + k_{yy}\frac{\partial^2 T}{dy^2} + k_{zz}\frac{\partial^2 T}{dz^2} + \dddot{\phi}$$

where T is the temperature, t is the time, x, y and z are the spatial coordinates, k_{xx}, k_{yy} and k_{zz} are the thermal conductivities, ρ is the density, C_p is the specific heat and $\dddot{\phi}$ is the heat source term. The heat source is modelled using a Gaussian model, which is the most widely adopted model that uses the symmetrical distribution of laser irradiance across the beam (assuming the irradiance is symmetrical about their propagation direction). This work uses an approximation of the heat source used by Shi et al. [21], expressed as:

$$\dddot{\phi} = 0.864\alpha \frac{P}{\pi r^2}$$

where P is the power of the laser beam, α is the laser energy absorptance of the material and r is the spot radius.

The calculations on the time-dependent temperature distribution during the SLM process were performed with the FE software ANSYS Ver. 14.0. Ansys solves the general energy balance equation in the