Materials and Design 106 (2016) 321–329

Contents lists available at ScienceDirect

Materials and Design

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

Evolution of grain structure during laser additive manufacturing. Simulation by a cellular automata method

A. Zinoviev [a,b], O. Zinovieva [a,b,*], V. Ploshikhin [a], V. Romanova [b,c], R. Balokhonov [b,c]

[a] Airbus Endowed Chair for Integrative Simulation and Engineering of Materials and Processes, University of Bremen, Am Fallturm 1, TAB, 28359 Bremen, Germany
[b] Institute of Strength Physics and Materials Science, Siberian Branch of the Russian Academy of Sciences, Pr. Academicheskii 2/4, 634021 Tomsk, Russia
[c] National Research Tomsk Polytechnic University, Pr. Lenina 30, 634050 Tomsk, Russia

ARTICLE INFO

Article history:
Received 10 April 2016
Received in revised form 27 May 2016
Accepted 31 May 2016
Available online 31 May 2016

Keywords:
Laser additive manufacturing
Grain growth
Solidification
Cellular automata
Evolution of grain structure

ABSTRACT

We have developed a two-dimensional numerical model to simulate the evolution of grain structure observed during the laser additive manufacturing process. A cellular automata method is used to describe grain growth. The Goldak heat source model is adopted to calculate the heat input during laser melting. A selective laser melting process which involves sequential deposition of powder layers on a polycrystalline substrate followed by their melting is examined. The influence of the heat source parameters on the evolution of grain structure is discussed. The simulation results are shown to be consistent with the experimental data describing the main characteristics of the grain structure.

1. Introduction

Additive layer manufacturing (ALM) is a relatively new and promising technology that has seen rapid development due to its successful application in fabrication of complex three-dimensional (3D) parts with no need for pre-production costs, expensive tools, multi-component assembly, and so forth. A wide range of applications, including medical, aerospace, defense, and automotive industries, have benefited from the foregoing approach [1–3].

The term "additive layer manufacturing" is related to several types of additive manufacturing processes that differ by ways of layer deposition [2]. Among them are extrusion deposition (fused deposition modeling), metal wire processes (electron beam freeform fabrication), binding of granular materials (selective laser melting), etc. The ALM technique studied in this work is selective laser melting (SLM) of metal powders by a focused laser beam in a layer-by-layer fashion.

In recent years, the SLM has received a great deal of attention of scientific and engineering communities. Different SLM aspects have been studied extensively, including the thermal processes involved in laser melting [4–10], microstructural evolution [10–13], mechanical properties of the SLM-produced materials [12–14], and the like. However, the use of the SLM approach is still quite limited due to certain drawbacks suffered by this technique. One of the main problems is a strong microstructural inhomogeneity of the SLM-produced parts [3]. Researchers studying microstructures formed by laser additive manufacturing (see, for example, [3,13,15]) observed bimodal grain structures consisting of large elongated columnar grains and a fine-grained region. The SLM process was shown to give rise to crystallographic texture resulting in strong anisotropy of the mechanical properties of the specimens produced [10–14]. Thus it is a challenge to control the microstructural evolution induced by the SLM process to produce tailored components.

The characteristics of the SLM-produced microstructures are influenced by many factors, among which are the heat input rate, material properties, cooling rate, and laser scan strategy, which requires a good deal of time and routine work. With advances in computing capabilities, numerical simulations that allow for extensive parametric studies incurring moderate costs become an effective tool for an analysis and prediction of the microstructural evolution caused by additive manufacturing.

The overwhelming majority of theoretical works has been devoted to finite element (FE) simulations of the SLM process aimed at analyzing the temperature [4–10,16] and velocity fields [10] and residual stress accumulation [5,16]. A comprehensive bibliography of publications on the modeling and simulation of laser additive manufacturing can be found in [1].

There is sparse literature on grain growth modeling for laser additive manufacturing. Marion et al. [17] offered a 3D FE model accounting for thermal and metallurgical aspects of additive manufacturing. While

* Corresponding author at: Airbus Endowed Chair for Integrative Simulation and Engineering of Materials and Processes, University of Bremen, Am Fallturm 1, TAB, 28359 Bremen, Germany.
E-mail address: zinovieva@isemp.de (O. Zinovieva).

http://dx.doi.org/10.1016/j.matdes.2016.05.125
0264-1275/

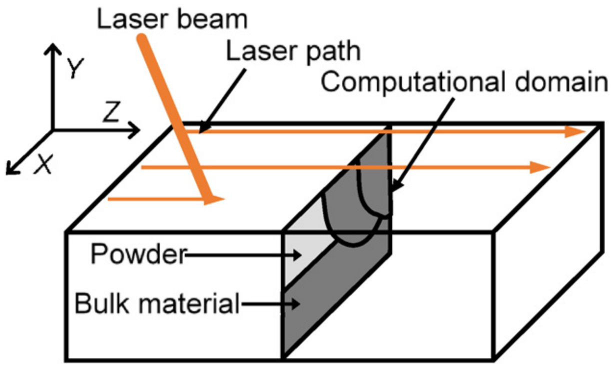

Fig. 1. Schematic of selective laser melting procedure.

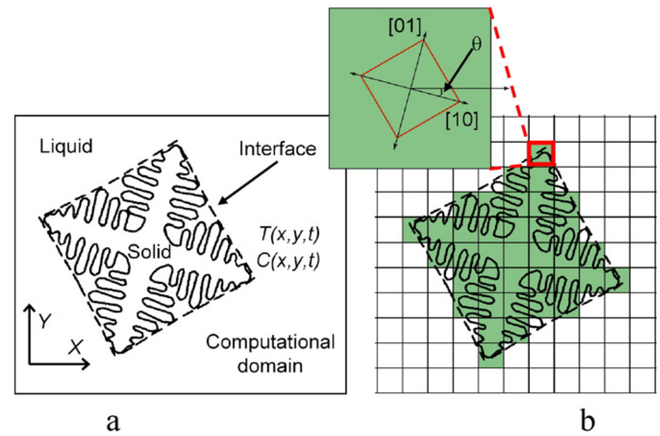

Fig. 3. Schematic of a computational domain in the 2D solidification problem: dendritic grain growth in the melt (a) and CA representation (b).

grain structure was not explicitly introduced in the model, allowance was made for phase transformations developing in laser additive manufacturing. Zhang et al. [18] constructed a predictive cellular automata (CA) FE (CAFE) model to study the mesoscopic morphological evolution of type SS 316 steel subjected to laser-assisted metal deposition. The same CAFE model based on the approach developed by Rappaz and Gandin [19] was adopted in [20] to simulate grain growth observed during electron-beam melting. Bauereiß et al. [20] examined melting of metal powders deposited on a metallic substrate followed by grain growth, whereas Zhang et al. [18] simulated grain nucleation and growth in the absence of original microstructure. Nie et al. [21] combined the FE method and a stochastic analysis to simulate the microstructure produced by laser additive manufacturing on the scale of individual dendrites. The model developed accounts for dendrite nucleation and growth, Nb segregation, and Laves phase particle formation during additive layer manufacturing in an Nb-bearing nickel-based superalloy. However, the model suffers from mesh anisotropy. In other words, the simulated dendrites are aligned with the global axis and exhibit the same orientation.

This paper presents the results obtained from simulation of the SLM-induced microstructural evolution. The simulation is based on a combination of the CA and finite-difference (FD) methods. Knowledge of the material microstructure, in its turn, enables the mechanical behavior of the parts so produced to be predicted.

2. Model description

2.1. Modeling approach to microstructure-based simulation of selective laser melting

The SLM process can be divided into several basic stages. First, a 3D computer-aided design (CAD) model of the part to be produced is developed and sliced into a certain number of thin cross-sectional layers. The model is then transferred to an SLM machine for the actual construction of the part. A thin layer of a metal powder is deposited on a substrate inside a closed process chamber. A high-power laser beam selectively melts the powder which subsequently solidifies reproducing the cross section of the CAD model. Then the substrate is lowered by one layer thickness and a new powder layer is deposited. The process is repeated until the manufacturing of the part is completed.

To investigate the SLM-induced microstructural evolution, we begin with simulation of original grain structure of a polycrystalline substrate that usually has an equiaxed configuration. For this purpose, use is made of a solidification model relying on the approach put forward by Rappaz and Gandin in [19] and implemented for the 2D case in [26]. Basically, the simulation procedure includes the following steps: (i) calculation of the temperature field; (ii) simulation of grain nucleation; and (iii) calculation of the solid phase increment. Since grains are assumed to nucleate and grow in a uniform temperature field, the final microstructure is equiaxed.

Once the initial substrate microstructure is generated, the repetitive stepwise SLM process is simulated. A powder layer is deposited on the substrate. The powder is treated as a continuous medium, and effective material properties are used to describe the response of the powdered material to thermal exposure. The computational domain which is a 2D cross section of the powder layer deposited on the substrate lies in the *XY* plane (Fig. 1), where the *Y*-axis is parallel to the specimen build direction. A focused high-power laser beam moving along the *Z*-axis transverses the 2D domain and melts the substrate together with the injected powder.

After each laser pass, the part is cooled down to room temperature, the generated melt pool solidifies, and the laser beam returns to the initial position, moves along the *X*-axis with a given step, and then begins its path along the *Z*-axis again. Dynamic evolution of the microstructure is described by the solidification model under consideration. On laser irradiation of the powder layer another powder layer is deposited and the SLM process is repeated until a specified number of layers are built.

Fig. 2 shows one simulation step of grain growth in selective laser melting. In addition to the material properties and model parameters,

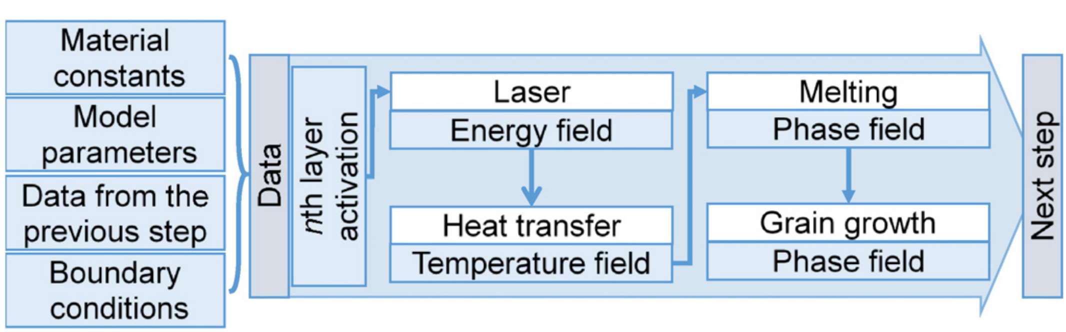

Fig. 2. Schematic of one simulation step of grain growth during selective laser melting.