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Modeling and Experimental Validation of the Electron Beam Selective Melting Process

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ABSTRACT

Electron beam selective melting (EBSM) is a promising additive manufacturing (AM) technology. The EBSM process consists of three major procedures: ① spreading a powder layer, ② preheating to slightly sinter the powder, and ③ selectively melting the powder bed. The highly transient multi-physics phenomena involved in these procedures pose a significant challenge for *in situ* experimental observation and measurement. To advance the understanding of the physical mechanisms in each procedure, we leverage high-fidelity modeling and post-process experiments. The models resemble the actual fabrication procedures, including ① a powder-spreading model using the discrete element method (DEM), ② a phase field (PF) model of powder sintering (solid-state sintering), and ③ a powder-melting (liquid-state sintering) model using the finite volume method (FVM). Comprehensive insights into all the major procedures are provided, which have rarely been reported. Preliminary simulation results (including powder particle packing within the powder bed, sintering neck formation between particles, and single-track defects) agree qualitatively with experiments, demonstrating the ability to understand the mechanisms and to guide the design and optimization of the experimental setup and manufacturing process.

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1. Introduction

Electron beam selective melting (EBSM) is a promising additive manufacturing (AM) technology for metallic components. It is capable of manufacturing components with complex geometry, and opens up new avenues for locally manipulating chemical compositions and mechanical properties as well. For example, Yang et al. [1] manufactured auxetic lattice structures with negative Poisson's ratios, and Ge et al. [2–4] manufactured functionally graded Ti-TiAl materials.

There are three main fabrication procedures in EBSM [2], as shown in Fig. 1.

(1) Spread one layer of powder on a preheated platform or previous layer. The layer thickness can vary for different layers. For each layer, the mixture ratio of the several different types of powder can be designed and tailored in order to allow the chemical compositions to be manipulated.

(2) Preheat the powder bed to make the powder slightly sintered. This helps prevent powder scattering, which may even lead to build failure.

(3) Selectively melt the powder bed. The beam power and scan speed are key factors that greatly influence the final part quality.

Although the basic principle of EBSM is rather straightforward, the actual processes consist of multiple physical phenomena such as powder particle packing, heat transfer, phase transformation, and fluid flow, and a number of factors influence the process and fabrication quality. There are a considerable number of fundamental physical mechanisms in each fabrication procedure to be understood

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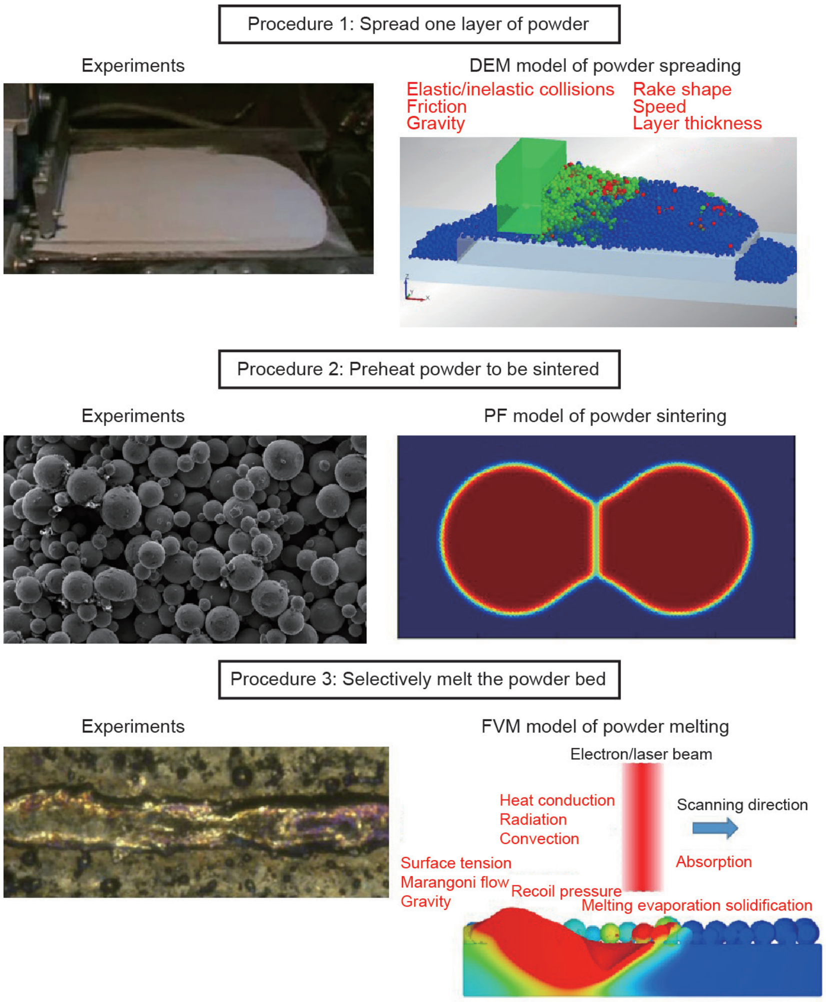

Fig. 1. Experiments and models of all procedures in the EBSM process. DEM: discrete element method; PF: phase field; FVM: finite volume method.

in order for optimal process parameters to be selected to ensure the fabrication quality. For example, the questions of how to improve the packing density of the powder bed in the powder-spreading procedure, how to achieve the optimal coalescence state of the powder bed in the preheating procedure, and how to avoid the balling effect and reduce single-track non-uniformity are all meaningful research topics.

Most previous studies focused on the melting procedure rather than on the other two procedures. Few studies have been done to comprehensively model all the manufacturing procedures. A few powder-scale models resolving the randomly distributed particles in the powder bed have been developed to investigate the melting process of individual powder particles [5–7]. Körner et al. [5] employed the rain model to generate the powder layer and the two-dimensional (2D) lattice Boltzmann method (LBM) to model the powder-melting process. They studied the influence of the powder layer thickness and input energy on the successive consolidation process of multiple powder layers. Khairallah et al. [6] built a meso-scopic model for selective laser melting (SLM) in order to investigate the formation mechanism of pores, spatter, and denudation in the single-track formation process using the ALE3D multi-physics code. Qiu et al. [8] used the open-source code OpenFOAM to simulate the powder-scale melt flow in the SLM process in order to study the surface structure and porosity development. These models incorporated most of the driving forces of the molten pool flow, including surface tension, the Marangoni effect, and recoil pressure. In this work, we leverage modeling and experiments to advance the understanding of physical mechanisms in each of the three procedures (Fig. 1). The models are introduced in Section 2, and include a powder-spreading model using the discrete element method (DEM), a phase field (PF) model of powder sintering, and a powder-melting model using the finite volume method (FVM). Section 3 presents the experimental methods. In Section 4, experimental and simulation results for each procedure are presented and discussed. Finally, a brief summary is given in Section 5.

2. Models

Note that the notations in the three subsections apply only in the respective subsections.

2.1. Powder-spreading model

Spherical powder particles with diameters that follow a Gaussian distribution in the range of 30–50 μm firstly fall to the bottom under gravity to form a powder bed, covering the substrate with various thicknesses. The rake then moves from left to right to spread the powder (Fig. 1). The movement of powder particles is governed by the contact interaction and body forces.

The Hertz-Mindlin contact model is used. In a simple case where there are only two contact particles with radii R_1 and R_2, the contact forces in the normal and tangential directions consist of nonlinear deformation and damping, as given in Eq. (1) and Eq. (2).

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