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Multi-scale modeling of electron beam melting of functionally graded materials

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ABSTRACT

Electron Beam Melting (EBM) is a promising powder-based metal Additive Manufacturing (AM) technology. This AM technique is opening new avenues for Functionally Graded Materials (FGMs). However, the manufacturing process, which is largely driven by the rapidly evolving temperature field, poses a significant challenge for accurate experimental measurement. In this study, we develop a novel multi-scale heat transfer modeling framework to investigate the EBM process of fabricating FGMs. Our heat source model mechanistically describes heating phenomena based on simulation of micro-scale electron-material interactions. It is capable of accounting for the material properties and electron beam properties that depend on experimental setup. The heat source model is utilized in the thermal evolution model of individual powder particles at the meso-scale to elucidate the melting and coalescing processes for mixed powder particles of different materials and different sizes. Another meso-scale simulation is conducted to evaluate the effective thermal conductivity of the original powder bed for the macro-scale model. A macro-scale heat transfer model is developed, in which the coalescence state is tracked to determine the effective material properties of the powder bed. Predictions of molten pool size are compared against published experimental results for validation.

1. Introduction

Additive Manufacturing (AM) technologies for metallic components, including Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Laser Engineered Net Shaping (LENS), have been drawing increasing attention over the past decade. In addition to manufacturing components with complex geometry, an appealing potential of these powder-based AM technologies is opening new avenues of locally manipulating the chemical compositions and the mechanical properties. For example, Ge, et al. [1–3], manufactured functionally graded Ti-TiAl materials using EBM; a process schematic is shown in Fig. 1. In this paper, we perform an investigation into the driving mechanisms for the overall fabrication process of Functionally Graded Materials (FGMs).

The EBM process for FGM is very complex; however, the fabrication procedure mainly consists of four repeated steps [1].

1. Apply one layer of powder on a preheated platform. For each layer, we can design and tailor the mixture ratio of the two different types of powder (see Fig. 1), in order to manipulate the chemical compositions. In the experiments, atomized Ti-6Al-4V and Ti-47Al-2Cr-2Nb powders were used [1].
2. Preheat the powder bed to slightly bond the powder particles. This helps prevent powder scattering.
3. Selectively melt the powder bed using a focused electron beam to form the 2D cross section of the desired 3D geometry. The beam power and scan speed are key factors which greatly influence the final part quality. Scan strategies, including scan path and repeated scan, are also influential. In Ref. [1], the scan speed and hatch spacing were kept constant at 500 mm/s and 0.2 mm, respectively, and the scan was repeated three times with successive beam currents of 2 mA, 4 mA and 6 mA.
4. Move the platform down by one layer thickness. The layer thickness can be adapted depending upon the desired geometry

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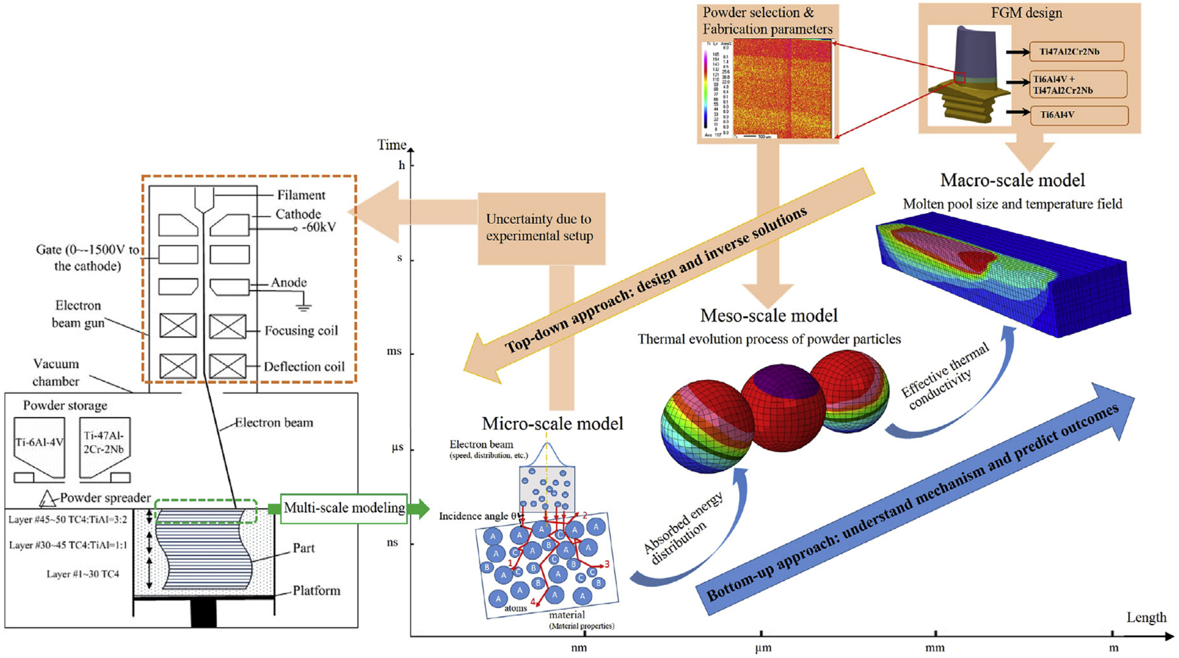

Fig. 1. Schematic diagram of proposed multi-scale modeling framework.

to achieve both high fabrication quality and short build time. In the experiments [1], the layer thickness was fixed at 100 μm.

The efficacy of fabricating FGMs is largely determined by melting and coalescing of the two different types of powder particles. The temperature field regulates the process. It not only directly determines the melting and solidification process but also influences the molten pool flow. However, it is difficult to accurately measure the temperature field in experiments: the peak temperature is very high (up to the boiling temperature of the metal) and the thermal gradient and heating/cooling rates are extremely large (up to 10^6 K/m and 10^6 K/s [4], respectively). The fabrication parameters for a qualified functionally graded component are traditionally determined through a long and costly experimental trial-and-error process. Effective numerical heat transfer modeling of the process has become a powerful tool for understanding and optimizing the EBM process [5], thereby reducing the extent of required experimental studies.

The macro-scale heat transfer models for SLM and EBM have been extensively investigated to calculate the temperature field and history, based on which a few more characteristics such as thermal stress [6] and microstructure [4] can be further predicted. A comprehensive review is given by Ref. [7]. The basic principle is to treat the powder bed as a reduced-density, low-thermal-conductivity continuum material [8].

A few powder-scale models resolving the randomly distributed particles in the powder bed have been developed to investigate the evolution process of individual powder particles [9–11]. Körner et al. [9] employed the Lattice Boltzmann Method (LBM) to study the successive consolidation process in powder layers. Khairallah et al. [10] developed a meso-scopic model to investigate the formation mechanism of pores, spatter and denudation using the ALE3D multi-physics code. The model incorporated surface tension, Marangoni effect and recoil pressure. However, both of these codes are not as accessible to the AM research community as open-source or commercialized codes, and the computation expense of these models can be up to the order of 100,000cpuh [12], which is considerably beyond the affordability of most AM research groups. Therefore, while these models provide insight to the physical mechanisms, they are not feasible in a concurrent design sense.

Most of the aforementioned models are focused on single material fabrication processes, and few studies have been done to provide insights of the fabrication process of FGMs. Moreover, most of the electron beam heat source models are either approximated as surface heat flux or assumed to be volumetric energy input similar with the molten pool shape, lacking a strong physical foundation.

In this study, we present a multi-scale modeling framework to understand and optimize the manufacturing process of FGMs at various scales. It consists of a new heat source model derived from the micro-scale electron-material interaction simulations, a heat transfer model for individual powder particles at the meso-scale, and a homogeneous macro-scale model. The framework is outlined in Fig. 1. The heat source model is material dependent and experimental setup specific. Since it incorporates the physics of the system, this model has obvious application to process design; other models, e.g. those based on molten pool shape, do not. To the best of our knowledge, this is the first multi-scale model specifically for the FGM fabrication process. Moreover, the computations can be done with a typical desktop or laptop making it a reasonable task. This means that the models can be used to rapidly provide fabrication parameter selection guidelines.

Körner et al. [9] demonstrated that the consolidation of powder particles is limited by thermal diffusion rather than molten material flow. These simulations showed that the melted portions of powder particles reshape to coalesce immediately after the liquidus temperature is reached. From this observation, we assume that if the mixed powder particles of different materials reach the liquidus temperature then the chemical compositions evenly mix. This assumption precludes the necessity of capturing molten pool flow and chemical element diffusion, since the details of the mixing process are not directly topical.

In Section 2, we introduce a new, mechanistic heat source model, which is material-dependent and experimental setup