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Multi-physics modeling of single/multiple-track defect mechanisms in electron beam selective melting

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ABSTRACT

Metallic powder bed-based additive manufacturing technologies have many promising attributes. The single track acts as one fundamental building unit, which largely influences the final product quality such as the surface roughness and dimensional accuracy. A high-fidelity powder-scale model is developed to predict the detailed formation processes of single/multiple-track defects, including the balling effect, single track nonuniformity and inter-track voids. These processes are difficult to observe in experiments; previous studies have proposed different or even conflicting explanations. Our study clarifies the underlying formation mechanisms, reveals the influence of key factors, and guides the improvement of fabrication quality of single tracks. Additionally, the manufacturing processes of multiple tracks along S/Z-shaped scan paths with various hatching distance are simulated to further understand the defects in complex structures. The simulations demonstrate that the hatching distance should be no larger than the width of the remelted region within the substrate rather than the width of the melted region within the powder layer. Thus, single track simulations can provide valuable insight for complex structures.

1. Introduction

Additive Manufacturing (AM) technologies have proven to be very promising in recent years with some of the advantages being the ability to fabricate parts in complex shapes [1], manipulating the chemical compositions [2] and tailoring the microstructures and mechanical properties for specific applications [3]. The powder-bed-based AM technologies, e.g., Selective Laser Melting (SLM) and Electron Beam Selective Melting (EBSM), are very promising metallic AM technologies. They possess the unique capability to manufacture lightweight cellular structures and thin-wall components [4,5] for applications including bio-medical implants and the aerospace and automotive industries. For instance, auxetic lattice structures with negative Poission's ratios [6], which are manufactured by EBSM, possess appealing potential as energy dampening structures to enhance vehicle safety.

However, the unsatisfactory quality of the final product caused by defects formed during fabrication is a major bottleneck, hindering the wide industrialization of the AM technologies [7] even though the fundamental concepts and ideas of AM were proposed more than twenty years ago [8]. For instance, surface roughness is an important consideration for aerospace applications, since it plays a large role in the mechanical performance such as fatigue life. Although post-machining can be performed on additively manufactured products to improve final qualities such as surface roughness, these processes become increasingly difficult as the product geometries become more complex. Thus, the best solution is to ensure sufficient quality of as-built products.

The basic principle of SLM or EBSM is to employ a laser/electron beam to selectively melt the metallic powder bed and deposit material along the designated scan path to build the desired complex shape in a layer-by-layer fashion. A single track is the fundamental building unit. However, defective single tracks such as discontinuous (Fig. 1 (a)) and nonuniform single tracks (Fig. 1(b)) rather than the desired ideally straight tracks are often observed, which negatively affect the surface finish and mechanical performance. Therefore, it is important to understand the formation mechanisms of single track defects and their dependence on

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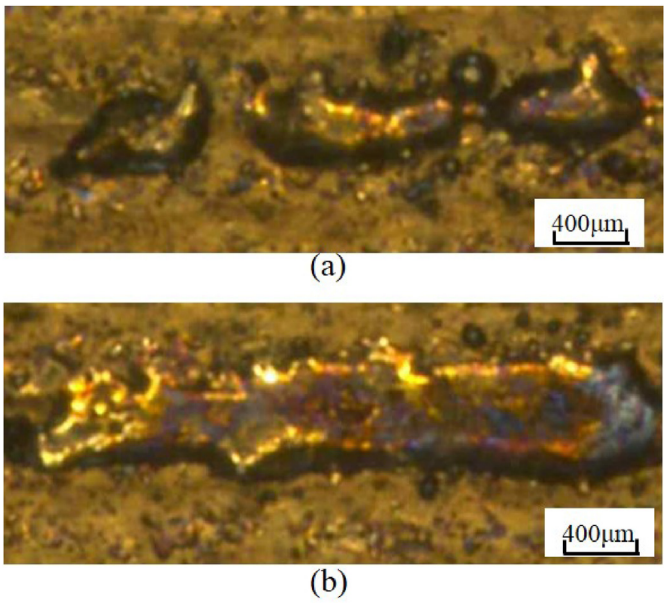

Fig. 1. Experimental images of (a) a discontinuous single track due to balling effect and (b) an nonuniform single track.

process parameters in order to improve the as-built product quality by SLM or EBSM.

Previous investigations [9–11] proposed different and even conflicting mechanisms of the "balling" effect and single track nonuniformity. Childs et al. [9] and Yadroitsev et al. [12] attributed the formation of single track nonuniformity and discrete droplets in SLM to the Plateau-Rayleigh capillary instability of the molten liquid based on theoretical analysis of the experimental results. Dai and Gu [10] employed the Finite Volume Method (FVM) to model the flow of the molten pool in SLM, and observed that the thermo-capillary force and the recoil pressure induced by evaporation were the major driving forces. The aforementioned models treated the powder bed as a continuum, and the effect of discrete powder particles as well as the formation process of the continuous molten pool was neglected.

Körner et al. [11] developed a 2-D mesoscopic model employing the Lattice Boltzmann Method (LBM). Their simulations revealed that the surface tension force between the molten liquid and the unmelted powder prevents the formation of a continuous molten pool and dominates the "balling" effect instead of flow instability. However, these 2-D simulations ignore the influence of the third dimension and enforced multiple simplistic assumptions while the real process is not symmetric and inherently complex in all directions. For instance, the surface tension force in the third dimension cannot be incorporated in 2-D simulations, thus the prediction of surface morphology is not physically representative of the actual process. Khairallah et al. [13] performed 3-D mesoscopic simulation of the selective laser melting process employing the ALE3D code. They attributed the anatomy of a melt track to the flow breakup.

In this study, we build a 3-D powder-scale multi-physics model using the Finite Volume Method (FVM) to predict the evolution process of discrete powder particles, which is difficult if not impossible to experimentally observe. Our model not only provides a 3D analysis, but is linked to more physically relevant models including the packed powder bed generation model and a mechanistically informed heat source model.

This study aims to identify the underlying physical mechanisms of major single track defects, including the balling effect and single track nonuniformity. The influence of some key factors is investigated to shed light on approaches to avoid the balling effect and reduce single track nonuniformity. Furthermore, multiple-track simulation results are presented to further advance our understanding of how current and previously melted layers interact with each other to build complex products.

2. High-fidelity powder-scale model

In order to reveal the physical mechanisms, a Computational Fluid Dynamics (CFD) model resolving individual powder particles is developed. The simulation domain consists of one layer of powder particles and a substrate. The size distribution of the powder particles is taken from experimental measurements, which is close to a normal distribution. The powder layer is generated by modeling a rake being pushed over a powder bed using the Discrete Element Method (DEM) [14]. This physically resembles the experimental powder bed packing process and does not require additional post-processing that would be required of other models such as the rain drop method [11]. The modeled packing density is close to that observed in experiments.

The melted material flow is assumed to be incompressible laminar flow. The thermal expansion of the melted material is ignored [15]. The mass density of the material (ρ) is set to be constant, and the buoyant force is ignored. The governing equations are mass continuity, momentum conservation and energy conservation given as follows:

$$\nabla\cdot(\rho\vec{v}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\otimes\vec{v}) = \nabla\cdot(\mu\nabla\vec{v}) - \nabla p + \rho\vec{g} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla\cdot(\rho\vec{v}h) = q + \nabla\cdot(k\nabla T) \tag{3}$$

where $\vec{v}$ and $\vec{g}$ denote the velocity vector and gravitational acceleration vector, respectively. Additionally, μ is the viscosity, p is the pressure, k is the thermal conductivity, and T is the temperature. In Eq. (3), $h = cT + (1-f_s)L$ is the specific enthalpy, where c, L and f_s are the specific heat, latent heat of melting, and fraction of the solid, respectively. The solid phase fraction ($f_s = \frac{T-T_s}{T_l-T_s}$) is assumed to be a linear interpolation of the temperature during the phase transition range between the solidus temperature T_s and liquidus temperature T_l. The solid phase is modeled using a viscosity-based approach. A constant finite viscosity larger than that of the liquid phase is assigned to the solid phase. Material viscosities that are between the liquidus/solidus temperature are calculated as a function of the solid-fraction f_s weighted average of the viscosities of the liquid and solid phases.

The surface tension effect is treated as a traction boundary condition on the free surface. Moreover, the surface tension coefficient is set to be temperature-dependent, and Marangoni effects are accounted for. Thermally, the boundary conditions are surface radiation and the heat loss due to evaporation. The initial temperature of the simulation domain is set to be 873 K, to incorporate the preheating procedure.

The commercial software FLOW-3D v10.1 is used to solve all the governing equations, in which a structural Eulerian mesh is used and the FVM is employed. The Volume of Fluid (VOF) method [16] is applied to track the free surface. As given in Eq. (4), the phase fraction (F) in each cell is calculated, while the velocity ($\vec{v}$) is obtained from the solution of the momentum equation given by Eq. (2). Based on the phase fraction, the free surfaces can be reconstructed in each time-step.