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Parametric investigation of microstructure after laser melting of metal powder layer

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Abstract

Powder shrinkage, low heat conductivity of powder layer and self-consistency of all equations are taken into account in the developed selective laser melting model. New marker function is used to account for thermal properties of the powder layer. Shrinkage speed is incorporated into the equation for free boundary evolution as a porosity dependent source term. Average crystalline size reduction is shown with the scanning speed increase and its growth - with laser power increase. Crystalline size is shown to grow with the powder height only with presence of the overhang effect. The results can be used for processing window estimation of powder layer laser melting as regards the required microstructure.

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1. Introduction

Selective laser melting of metal powder is a promising additive technology which gives an opportunity for free form fabrication of metal parts and coatings by the layer by layer technic [1]. SLM is demanded for a high quality built-up layer, powder and whole process efficiency to rival traditional manufacture technology. Numerical modeling of SLM has been the focus in the literature [2,3,4] as a cost-effective method to find processing parameters

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which result in the required functional quality of a built-up layer (geometry, microstructure, etc.).

In spite of the fact that SLM technology has been known for a long time and certain phenomena are well investigated [5,6,7,8] insufficient attention is paid to phase change modeling and investigation of the microstructure thus far. Existing models consider phase change in a simplified manner [9], without specific character of high cooling and heating rates. More complex crystallization models are often not self-consistent for phase change, heat-mass-transfer and free boundary evolution.

The small grain size is known to result in increased wear resistance and hardness of produced part [10]. Hence, the knowledge of microstructure is vital for improving SLM technology. The aim of this paper is to investigate numerically the self-consistent heat/mass transfer, kinetics of phase change and optimization of the SLM process with regard to average crystalline size.

2. Basic equations and methods

The model deals with heat/mass transfer in multi-phase system: gas – metal (liquid metal – solid substrate – powder). The main attention is devoted to self-consistency of the phenomena: heat conductivity, hydrodynamics, free surface movement and rapid crystallization of a built-up layer.

It is a difficult challenge to take into account all of the phenomena, so certain processes are accounted for where there is direct influence on the microstructure. Balling effect is typical for SLM in general. It is connected with Rayleigh-Plato instability which can occur in cylinder with length to radius ratio more than π. The powder is supposed to be well wetted and the process occurs in the absence of balling effect. Compact fine-dispersed powder is modeled and infiltration effect is not taken into account.

Macro model is based on [11] where the main movement sources are the thermocapillary and capillary forces [12] which are incorporated into the momentum equation as volume sources [13]. The S-CLSVOF method [14] is used for free boundary capturing which has been verified [15] for multiphase systems with thermocapillary forces. PISO algorithm is used for pressure velocity coupling [16]. Melting is supposed to occur isothermally and hydrodynamics in phase change region is modeled by a porosity layer [17]. Additional marker function is introduced to account for low heat conductivity of powder layer. The self-consistent governing equations for heat transfer and fluid flow at SLM are the following:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathrm{u}) = 0 \tag{1}$$

Energy conservation equation:

$$c\rho\frac{\partial T}{\partial t} + c\rho\nabla(uT) = div\left(\lambda\nabla T\right) + \alpha_{beam} q\delta(\varphi) + \rho(1-f_l)\Delta c\frac{\partial T}{\partial t} - \rho L\frac{\partial f_l}{\partial t} \tag{2}$$

Momentum conservation equation:

$$\frac{\partial \rho u_i}{\partial t} + \nabla(\rho \mathrm{u} u_i) = div\left(\mu\nabla u_i\right) - \frac{C_{big}(1-f_l)^2}{f_l^3 + C_{small}} - \frac{\partial p}{\partial i} + \nabla T\frac{\partial \sigma}{\partial T} i \tag{3}$$

Free boundary evolution equation:

$$\frac{\partial \alpha}{\partial t} + \nabla\cdot(u\alpha) = -F_{porosity}\left|\nabla\alpha\right| \tag{4}$$

Here t is time, p is pressure, T is temperature, c is specific heat capacity, ρ is density, λ is thermal conductivity, f_l is volume fraction of liquid, u_i is velocity component, $i = x, y, z$; μ is viscosity, α is volume fraction of metal, $F_{porosity}$ is free boundary velocity due to shrinkage effect, C_{big} and C_{small} are constants with corresponding larger (10^8) and smaller (10^{-6}) values, respectively.

The thermophysical properties for the solid-liquid-gas model are characterized by marker functions. Metal – air properties are distinguished by α:

$$\rho = \alpha\rho_m + (1-\alpha)\rho_g,$$

$$c = \alpha c_m + (1-\alpha)c_g,$$

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