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A multiscale nonequilibrium model for melting of metal powder bed subjected to constant heat flux

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ABSTRACT

A multiscale numerical model based on nonequilibrium thermal effect for melting of metal powder bed subjected to constant heat flux is developed. The volume shrinkage due to density change is taken into account. The nonequilibrium model is discretized by an implicit finite difference method and solved numerically using an iterative tri-diagonal matrix algorithm. The evolutions of powder bed surface temperature and various interfacial locations as well as the melting temperature range during the melting process are investigated. The results show that liquid region, upper and lower parts of mushy zone are formed on the top of unsintered zone as the melting progresses. The duration of the preheating stage shortens and the melting rate accelerates as the initial porosity or initial temperature increases while particle size has much less effect on the melting process. The parametric study shows the melting temperature range of the powder bed widens with increasing initial porosity, decreasing initial temperature or increasing particle size.

1. Introduction

Selective laser sintering (SLS) is a rapid prototyping and additive manufacturing technology that creates three-dimensional freeform and nearly full-density parts via layer-by-layer sintering or melting of metal powders induced by a directed laser beam [1–5]. For metal powder-based SLS process, the loose powder bed is heated and melted into a liquid pool by the incident laser beam, and then the liquid metal resolidifies as the laser beam moves away. Melting and resolidification process have significant effects on the quality and precision of final products [5].

Many investigations of metal powder melting and solidification have been carried out by numerical and experimental methods to understand mechanism of the SLS process. Fischer et al. [6] performed SLS experiments on titanium powder subjected to a nanosecond Nd:YAG laser with two different energy coupling mechanisms. Gusarov et al. [7] analyzed the effects of powder structural parameters on effective contact conductivity of SLS powder bed using a spherical coordinate numerical model. Konrad et al. investigated analytically melting and resolidification of metal powder subjected to nanosecond laser heating based on the powder bed model [8] and particle model [9], respectively. Kim and Sim [10] studied numerically thermal behavior and fluid flow during the transient and steady state laser melting of alloys using the enthalpy and apparent capacity methods. Pak and Plumb [11] developed both constant volume and constant porosity models for melting of a two-component powder bed.

One major challenge of SLS is the balling phenomenon [12], in which a series of spherical grains with diameters approximately equal to that of the laser beam are formed because the melted powder particles stick each other due to surface tension. There are several technologies to overcome the balling phenomenon. one of which is direct metal laser sintering (DMLS) that can manufacture directly densified metal parts subjected to laser beam with lower scanning speed in the sintering surroundings filled with protective gas [13]. More investigations about the sintering behavior, microstructural features and heat transfer mechanism of various metal powders of DMLS were carried out [14–17]. The metal powder can be completely molten without balling phenomenon and the final densified parts do not need post-processing.

During the DMLS process, the melting accompanying with shrinkage due to significant density change makes it very complex. The effects of shrinkage on melting and resolidification during the DMLS process have been investigated using different models and methods. Zhang and Faghri [18] analytically solved melting of mixed powder bed with constant heat flux heating based on a one-dimensional model considering shrinkage. Xiao and Zhang [19] investigated numerically the shrinkage effects on temperature distribution and solid–liquid interface location of DMLS using the

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Nomenclature

w	liquid velocity, m/s
W	liquid dimensionless velocity
T_m	melting temperature, K
T_i	initial temperature, K
q''_0	constant heat flux, w/m^2
c_p	specific heat, kJ/(kg · K)
h_{sl}	latent heat, kJ/kg
f	mass fraction

Greek symbols

ε_0	initial porosity
φ	volume fraction
θ	dimensionless temperature
k	thermal conductivity, w/(m · K)
α_P	thermal diffusivity $k_l/(\rho_P c_P)$, m^2/s

Subscript

g	gas
s	solid
l	liquid
p	particle
pl	liquid phase of particle
ps	solid phase of particle
0	heating surface

three-dimensional convection model. Childs et al. [20] studied density change and melting depths of single layer and multi-layer DMLS process based on experimental and three-dimensional numerical methods. Dai and Shaw [21] presented a three-dimensional thermomechanical finite element model to investigate the transient temperature, transient stresses, and residual stresses of powder bed. The numerical model encompassed the effects of density and temperature changes on the thermal conduction, radiation and natural convection. Kim et al. [22] investigated heat transfer and fluid flow of the molten pool in stationary gas tungsten arc welding considering shrinkage and convection induced by surface tension, buoyancy, and impinging plasma arc forces. Xiao and Zhang analytically solved the problems of partial melting [23] and complete melting [24] for powder bed with constant heat flux. The results showed that the shrinkage effects on the geometry and temperature distribution during the DMLS process were significant.

In contrast to melting and resolidification with well-defined melting point in conventional sintering, phase change for DMLS, from a macroscopic point of view, occur gradually within a temperature range of (T_{sm}, T_{lm}) due to the nonequilibrium thermal phenomenon [1], in which the temperature of the particle surface is much higher than that of the particle core because the energy heats up at the surface caused by the very high intensity of the laser beam. Therefore, during the DMLS process the mean temperature of the melting particle is within a range of temperature adjacent to the melting point, depending on the melting degree and temperature distribution of the particle. Gu and Shen [25] studied experimentally the development of WC-Co particulate reinforcing Cu matrix composite material using direct laser sintering and found the nonequilibrium effects played important roles on the melting process. Xiao and Zhang [23] developed an analytical model considering nonequilibrium thermal phenomenon in DMLS, but the temperature range was assumed to be known prior.

In order to understand the nonequilibrium thermal effects on melting of metal powder bed during the DMLS process, a multi scale nonequilibrium model for melting with constant heat flux considering shrinkage is developed in the present study. The model is based on nonequilibrium thermal effect that the melting temperature range of the powder bed is dependent on the degree of melting and temperature distribution of the particle. The effects of particle size, initial temperature and initial porosity of the powder bed on temperature distribution and melting geometry will be systematically investigated.

2. Problem statement and formulation

For the problem under consideration, the time scale of thermal diffusion within particles can be obtained by the time constant $t_p = \rho_p c_p V_p / h_f A_p$ [26], where V_p, A_p are volume and surface area of the particle and heat transfer coefficient h_f can be estimated by Nusselt number for heat conduction [26]; the time scale of the particle is in the order of 10^{-6} s. On the other hand, the time scale of the laser sintering problem can be estimated based by the pulse duration (10^{-7} s) or the thermal penetration time of one particle depth [23] (about 10^{-7} s). The time scale of the particle is larger than that of the macroscopic problem, so a multi scale model is required and established for the melting of metal powder bed during the DMLS process.

The multi scale model is consistent of two sub-models: one for powder bed level based on continuum assumption and the other one at the particle level to obtain the range of phase change temperature. Under the powder bed level model, the powder bed is treated as continuum that melts in a range of temperature; the temperature range depends on the degree of melting and temperature distribution in the particle. Meanwhile, the temperature distribution from the particle level model relates to the heat flux from the powder bed. Therefore, the multi scale nonequilibrium model is a coupled problem of the powder bed and the particle which can be solved iteratively.

2.1. Heat transfer in the powder bed

Fig. 1 shows the physical model for metal powder bed with constant heat flux. The heating flux is absorbed by the randomly packed metal powder bed ($z \geqslant 0$) with an initial porosity of ε_0 and initial temperature of T_i, which is below the melting point of the metal powder material T_m. During the DMLS process, the powder particle undergoes melting has a mean temperature adjacent to the melting point due to nonequilibrium thermal effects of DMLS process [1]. Under constant heat flux heating, the surface temperature of the powder bed increases and then melting occurs when the powder bed surface temperature reaches to the lower limit of the range of melting temperature, T_{sm}, instead of the melting point T_m. A mushy zone where the solid and liquid coexist is formed as the temperature increases continuously, finally the liquid zone appears on the top of the mushy zone when the surface temperature increases to the upper limit T_{lm}. Consequently, there are three regions of the entire powder bed: liquid zone, mushy zone and unsintered zone.

During the melting process, the liquid permeates into the void of the unsintered zone as the interstitial gas between solid particles is driven out, and the solid core in the mushy zone moves downward due to shrinkage. The shrinkage is completed when the gas volume fraction of the mushy zone decreases to zero, so the mushy zone can be divided into two sub-regions: the lower part with shrinkage and the upper part without shrinkage. For the lower part, gas, liquid and solid coexist. It is assumed that