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Finite element analysis of thermal behavior of metal powder during selective laser melting

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ABSTRACT

The thermal behavior during the selective laser melting of metal powders is a key issue to the product quality in 3D printing, so it is of benefit to the development of 3D printing industries to explore the heat transfer characteristics during the selective laser melting process. Based on the $TiAl_6V_4$ powder system, the energy conservation equation with a moving Gaussian energy source is developed, in which the temperature-dependent thermal physical properties of materials are taken into account. By means of the finite element methods, the temperature distribution and molten pool dimensions are presented, and the related modeling and numerical methods are validated by previous experimental and numerical works. The effects of the linear energy density, volume shrinkage, scanning track length, hatch spacing and time interval between two neighboring tracks on the temperature distribution and molten pool dimensions are obtained and analyzed. The results show that the increased laser power is superior to the reduced scan speed in thermal performance, which can improve the temperature distribution and molten pool dimensions. Shorter track, shorter hatch spacing and less time interval can lower the temperature gradient and increase the temperature of each track. The average temperature and dimensions of the molten pool are influenced by the volume shrinkage, which should be considered during the numerical simulation.

1. Introduction

In recent years, rapid manufacturing (RM) technology, as a novel method which can fabricate production cheaply and fast, has attracted more attentions. The selective laser melting (SLM) has become an increasingly developing approach of RM, and is widely applied to precise parts manufacturing [1,2]. Different from traditional methods, SLM technology makes use of high energy laser beam to selectively scan thin loose powder sliced layer from CAD model. After layer-by-layer scanning, the melting and solidification of powders take place in milliseconds. As a result, the final model with high mechanical properties will be shaped [3]. SLM can melt powder completely, and produce higher-density parts, which differs from another manufacturing technology, selective laser sintering [4,5].

SLM involves many complex processes of heat and mass transfer, including conduction, convection, radiation and evaporation. Previous studies have shown that the process parameters such as the laser power, velocity, preheating temperature and layer thickness are all the key issues to the final mechanical properties of SLM parts [6]. In order to reduce the defects such as balling and crack of parts, many works have been done to predict the temperature field and mechanical properties of SLM. Kolossov et al. [7] developed a three dimensional finite element model with consideration of temperature-dependent non-linear thermal properties of materials to study the temperature evolution in selective sintering of titanium powder, and the simulation results show a good agreement with experiment data. Gu and Shen [8] investigated two kinds of balling phenomena in metal laser sintering, showing that the balling defect can be reduced by adjusting the laser power, scan speed or layer thickness. A finite element model based on the powder bed was proposed by Hussein et al. [6], and the dimension of the molten pool at different scan speeds in SLM process was predicted. Gusarov et al. [9] pointed out that there was an interval scan speed at which the re-melted tracks were uniform in SLM process, and a high scan speed might lead to a balling. Dai and Gu [3] investigated the effects of linear energy density (LED) on temperature distribution, molten pool size and densification, showing

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Nomenclature

A	laser absorptivity of powder
c_p	specific heat (J kg^{-1} K^{-1})
d	hatch spacing (mm)
D_p	average diameter of the powder particles (m)
D_{melt}	molten pool dimensions
F	constant view factor
H	enthalpy (J m^{-3})
h	total heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_{eff}	effective thermal conductivity of powder layer (W m^{-1} K^{-1})
k_f	thermal conductivity of gas (W m^{-1} K^{-1})
k_r	thermal conductivity due to radiation(W m^{-1} K^{-1})
k_s	thermal conductivity of solid (W m^{-1} K^{-1})
l	length of scanning track (mm)
L	moving distance (mm)
LED	linear energy density (J m^{-1})
N_t	number of track
P	laser power (W)
r	distance from center of laser spot (m)
T	temperature (K)
T_m	melting temperature (K)
T_p	temperature of powder particles (K)
T_0	ambient temperature (K)
t	time (s)
V	scan speed (mm s^{-1})
x, y, z	coordinates, m

Greek symbols

α	Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
δ	layer thickness (μm)
ρ_{dense}	density of dense solid (kg m^{-3})
ρ	density (kg m^{-3})
φ	porosity of powder layer
φ_0	initial porosity
ω	radius of laser beam (m)

that a higher LED could increase the molten pool size and maximum temperature of the powder layer. Dai and Shaw [10] developed a model including the effect of powder-to-solid transition, and obtained the temperature and stress fields. Roberts et al. [4] took the process variables and multiple layers into account, and made clear the transient temperature history in multiple layers by using element birth and death technique. It has been known that volume shrinkage tends to occur due to the transformation from the powder to dense solid in SLM process [5], so Dai and Shaw [11] studied the temperature distribution of a three dimensional finite element model and proposed different criterions judging the state of element by taking volume shrinkage into consideration. Both complete and partial shrinkages were considered by Chen and Zhang [12], they found that the shrinkage was related to the volume fraction of gas in the liquid pool and loose powder. Loh et al. [13] made a detailed discussion about the molten pool size and temperature change with consideration of volume shrinkage and evaporation of powder layer. Yadroitsev et al. [14] provided a theoretical and technical basis for SLM process by exploring the links between SLM process parameters and geometrical characteristics of tracks, the results showed that the process parameters had different influences on the molten pool dimensions. Zhang et al. [15] studied the effect of the scan line spacing on fabricating porous $TiAl_6V_4$ implants, and proposed a suitable scan line spacing for high mechanical properties of implants. Li et al. [16] investigated the densification, microstructure evolution, and mechanical properties of metal glass during SLM process, providing a deep understanding of fabricating high-density and crack-free products. Zohdi [17,18] proposed a computational model and developed a solution algorithm to simulate the selective laser processing, by which a detailed analysis of additive manufacturing was made.

From the aforementioned studies can be seen that, LED determined by the laser power and scan speed [3,19] strongly affects the temperature field, thus plays an important role in the property determination of the parts. However, there is still no detailed analysis about how the laser power and scan speed affect the SLM process respectively. Besides, the changing trends of the molten pool size and temperature distribution when taking the volume shrinkage into account have not been investigated in detail. The impacts of the interval time between tracks on temperature distribution when the laser beam always moves in the same direction are also not clearly addressed in previous works. In this study, a computational finite element method based on a transient analysis is developed to predict the thermal behavior in SLM process, which is validated by previous computational and experimental results. The effects of the laser power, scan speed, scanning track length, time interval and hatch spacing between two neighboring tracks and the volume shrinkage on the temperature distribution and molten pool size are all investigated to clarify the thermal behavior of metal powders during selective laser melting.

2. Computational models

Finite element method is introduced to simulate the SLM process by providing non-linear transient temperature analysis. Due to the complexity of SLM, the following assumptions are made:

(1) The heat flux applied on the powder surface is assumed as a surface source because of the limited penetration depth [3];
(2) The porosity of material φ is in two levels, one is the initial porosity φ_0 for powders, and the other is zero for dense liquid and solid [20];
(3) Vaporization of material is ignored;
(4) Powder material is considered as a continuous medium. When the temperature is lower than melting point, the material is in a powder state, and there is a sudden change from the powder to liquid state at melting temperature [6].

2.1. Physical model

Fig. 1(a) schematically shows the SLM process, where a single 30 μm $TiAl_6V_4$ powder layer is deposited on the dense substrate. The ambient is full of argon to prevent oxidation, and the whole plate temperature is 100 °C (T_0). The heat flux from the laser beam with the Gaussian distribution is applied on the top surface of the powder layer, moving along the x-axis with a constant velocity. There are three kinds of Gaussian distributions, and the fundamental mode TEM_{00} is adopted here [4]. Scanning strategy is shown in Fig. 1(b), and five scanning tracks were investigated. The powder layer with the dimension of $3 \times 3 \times 0.03$ mm is placed on the dense substrate with the dimension of $3 \times 3 \times 1$ mm. In order to reduce the computational cost, the scanned powder area with the dimension of 1×0.5 mm is finely meshed with the hexahedral