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Role of scanning strategy on residual stress distribution in Ti-6Al-4V alloy prepared by selective laser melting

Jia Song[a], Wenheng Wu[b,*], Liang Zhang[a,*], Beibei He[b], Lin Lu[b], Xiaoqing Ni[a], Qianlei Long[b], Guoliang Zhu[c]

[a] Shanghai Engineering Research Center of 3D Printing Materials, Shanghai 200437, China
[b] Shanghai Research Institute of Materials, Shanghai 200437, China
[c] Shanghai Key Laboratory of advanced High-temperature Materials and precision Forming School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

Selective laser melting (SLM) is one of additive manufacturing (AM) technologies used for directly fabricating 3D metal parts with complex shapes. However, the residual stress and the resultant deformation issues lead to the distortion and failure of SLM fabricated parts and impede the further application of this technology. In this research, a combination of the finite element simulation and experimental verification is proposed to study the effect of scanning strategies on the thermal behavior and residual stress distribution. Two kinds of mechanical boundary conditions are selected to investigate its effect on the residual stress in the mechanical simulation. The transient thermal simulation results demonstrate that the scanning strategies take a great influence on temperature field, however, molten pool size is hardly affected by the scanning strategies. In terms of residual stress simulation, 15° rotate scan strategy generates the smallest stress among the all scan strategies studied in this research. This conclusion is confirmed by experimental results. In addition, although there is still a difference between the numerical simulation and experimental result, mechanical simulation gives satisfactory residual stress trend compared with experiments.

1. Introduction

Additive manufacturing technology is a novel method for fabricating the high-performance and complicated components directly [1–3]. Contrary to traditional subtractive manufacturing, due to its near net forming feature, additive manufacturing technology have attracted more and more attention [4–7]. The applications of products fabricated by additive manufacturing technology has demonstrated in many field, such as aviation, aerospace and medical areas. The typical commercial available additive manufacturing technology for alloys are selective laser melting (SLM), which is considered as one of the most potential technologies for near net forming. SLM process begins with the decomposition of three-dimensional CAD model into hundreds of layers [8,9], and then accumulates layer by layer using a selectively scanning laser beam [10–14].

Owing to incremental manufacturing mechanism, SLM technique has several advantages such as complete fusion, near-net forming, small heat affected region and complex structural design ability [15]. These merits greatly prompt the application potential of SLM technique in various fields. In the last decade, SLM technology has dealt with a good deal of commercial metallic matrix

* Corresponding authors.
E-mail addresses: wwhwwh2004@126.com (W. Wu), zhangliang@srim.com.cn (L. Zhang).

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materials and widely shown in the literature, such as Li et al. in case of aluminum-based materials, Zhang et al. for nickel-based superalloys and Zhou et al. in case of titanium-based alloys [16–18]. Among these alloys, Ti-6Al-4V is the most favorable and widely applied in aeronautic, astronautic and medical industries. This is due to its excellent mechanical and chemical properties, for instant, low density, excellent corrosion resistance, high specific strength, good toughness [15,19,20].

Although SLM technologies own many advantages compared with conventional manufacturing technique, it still faces several challenges. In the SLM process, high temperature gradients caused by rapid heating and cooling cycles of molten pool lead to many defects such as micro-cracks and thermal distortion resulted from process-induced residual stress [21]. These defects greatly hinder the wide application of SLM products. Hence, it is necessary to investigate high temperature gradients in the materials and the evolution mechanism of residual stress during SLM process. Nevertheless, the SLM process is an intricate physicochemical metallurgy process, such as thermal physical process between molten metal and solidified layer, thermal radiation on the melt surface, phase transformation and interaction between molten metal and powder [13]. These physicochemical process usually happens in extremely short time, so that traditional experimental method could not reveal clearly the evolution mechanism of the temperature distribution and residual stress field during and after SLM process.

To address these issues, several researchers have performed numerical simulation in order to investigate the thermal and mechanical process of SLM. A developed 3D model was proposed by Childs et al. to predict the temperature distribution of stainless steel powders during SLM process. Compared with experimental values, their simulation results demonstrated that numerical simulation was a useful tool to investigate the temperature field during SLM [22]. Dai et al. adopted a 3D finite element model to study the key factors that influencing the temperature field distribution. Their result shows that heat conductivity and coefficient heat conductivity of metal powder played a crucial role in the temperature field distribution [23]. A 3D mesoscopic model was developed by Zhang et al. to analyze the temperature field distribution of W-Ni-Fe material during SLM process. Their simulation results indicated that processing parameter took significant effect on the temperature field distribution [13]. Song et al. developed a 3D sequentially coupled finite element model to investigate the temperature field distribution of Ti-6Al-4V powder in the SLM process. According the numerical simulation results, they found a better processing parameter which could reduce the defects of part [15]. Cheng et al. recently utilized a novel 3D thermomechanical model to simulate residual stress and deformation of multilayer deposition with various scanning strategies in the SLM of In718 powder. Their simulation results demonstrated that the 45° line scanning case may reduce residual stress in both directions and has a smaller deformation in build direction among all tested cases [24]. Li et al. conducted three-dimension uncoupled thermomechanical simulation to investigate part deformation caused by scan pattern. Their simulations revealed that horizontal successive scan pattern can reduce substrate deformation than tested vertical or island scan pattern [25].

In present research, numerical simulations are carried out using finite element method. A moving Gaussian heat source, temperature dependent Ti-6Al-4V alloy properties, layer addition feature and different scanning strategies are considered in this research. The aim of this paper is to numerically analyze the effect of laser scanning strategies on the size of molten pool, temperature distribution, residual stress distribution and thermal deformation in the SLM process. Several experiments are performed in order to verify the model used in this research. The influence of different constraint conditions in the model in the residual stress distribution is discussed as well. The results in this research may provide an effective way to improve the quality of SLM parts through scanning strategy selection.

2. Finite element modeling method

2.1. Thermal modeling

To accurately simulate the laser penetration effect and capture the transient thermal transportation phenomenon in the SLM process, a moving Gaussian heat source distribution is used, which is proposed by Goldak et al. [26,27]. The conical volumetric heat source is expressed as follow:

$$q(x,y,z) = \frac{\eta\cdot 6\sqrt{3}Q}{hr^2\pi\sqrt{\pi}} exp\left(-\frac{3x^2}{r^2} - \frac{3y^2}{r^2} - \frac{3z^2}{h^2}\right) \tag{1}$$

where, the $q(x,y,z)$ is the heat flux density of point (x, y, z) in the coordinate system, Q is the laser absorption power of powder, η is the laser energy, r is radius of gaussian distribution surface circle district and h is the depth of Gaussian heat flux. A FORTRAN program is used in finite element model to control the laser scanning direction and magnitude of heat source.

For the three-dimensional conductive model, conservation of energy and Fourier's law are both considered in mathematics equation. So, the thermal energy balance equation in the model can be described as:

$$Q_L = Q_E - Q_c - Q_{CV} - Q_R \tag{2}$$

in which, Q_L, Q_E, Q_c, Q_{CV} and Q_R represent the addition of total energy, the absorption energy of powder bed of laser exposure, the energy loss of conduction, convection and radiation, respectively. The thermal equilibrium equation for three-dimensional heat transfer in a material with isotropic thermal properties can be written as:

$$\frac{\partial q}{\partial t} = \frac{k}{\rho C_P}\left(\frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 q}{\partial y^2} + \frac{\partial^2 q}{\partial z^2}\right) \tag{3}$$