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Heat transfer simulations of selective laser melting process based on volumetric heat source with powder size consideration

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ABSTRACT

Three-dimensional finite element heat transfer simulations with new volumetric heat source are performed to estimate the size of the melt pool cross-section during Selective Laser Melting (SLM). The simulations are based on a new volumetric heat source which takes into account the effect of the powder size distribution on the propagation of the laser energy through the depth of the metal powder layer. In modeling the volumetric heat source, a modified sequential addition method is used to construct the metal powder layer with different powder particle sizes and the absorptivity profile along the depth of the powder layer is then calculated by means of Monte Carlo ray-tracing simulations. It is shown that the peak melt pool temperature obtained in the present simulations (3005 K) is in better agreement with the experimental value than that obtained in previous simulation studies. Furthermore, the peak temperature is lower than the evaporation point of the powder particle layer, and is hence consistent with the stable melt track reported in experimental studies. To further confirm the validity of the proposed finite element heat transfer model, the simulation results obtained for the contact width between the melt pool and the substrate and the width of the powder-consumed band are compared with the experimental results and simulation findings presented in the literature. Finally, simulations are performed to predict the stability condition of a single scan melt track in the SLM process. The prediction results are shown to be consistent with the experimental findings.

1. Introduction

Laser based Powder Bed Fusion is an Additive Manufacturing process and Selective Laser Melting (SLM) is one of the equipment. SLM manufactures three dimensional (3D) parts by selectively melting specific areas of metal powder layers using controlled laser beam. The physical phenomena associated with SLM are highly complex, and include scattering and absorption of laser radiation in the packed powder bed, heat conduction, melting and fusion of the powder particles, the formation and solidification of the melt pool, and so on (Gusarov et al., 2009). According to the authors in (Gibson et al., 2010), the SLM processing parameters fall into four main categories, namely: (1) laser related parameters (i.e., the laser power and laser spot size); (2) scan related parameters (i.e., the scan speed, scan pattern, and scan spacing); (3) powder related parameters (i.e., the particle size distribution and powder material); and (4) temperature related parameters (i.e., the powder bed temperature and preheating temperature). These parameters are mutually interactive in the manufacturing process and have a profound effect on the mechanical properties of the final component. Consequently, relying on experimental trial-and-error methods to determine the optimal SLM processing conditions is extremely inefficient and time consuming (Khairallah and Anderson, 2014). Thus, simulation models for estimating the suitable parameters are commonly preferred.

In particular, one of the important issues of simulation models for SLM process is to predict the dimension of cross-section of melt pool. According to literature (King et al., 2014), the formation of melt pool is based on the conduction-melting and "keyhole-mode" melting regions. For comprehensively simulating the formation of melt pool's cross section in both conduction and keyhole-mode accurately, the authors in literature (Khairallah et al., 2016) proposed a fine-scale simulation model and this simulation employed laser ray tracing energy source to clarify the impact of Marangoni convection, vapor recoil pressure caused by evaporated metal, evaporative and surface cooling on the fluid flow in the melt pool during SLM process. However, the computational expense for this simulation is extremely high. In particular, the authors in this literature employed ALE3D massively-parallel code which can consume 100,000 cpu h (Khairallah and Anderson, 2014).

Accordingly, for avoiding high computational expense, different

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Finite Element Method (FEM) models have been proposed with certain assumptions to estimate the dimensions of the cross section of melt pool (i.e. contact width between melt pool and substrate, depth of melt pool). Some simplifications are listed as follows: (1) treated the powder bed as a homogeneous medium with effective thermal and optical properties; (2) the effect of Marangoni convection and vapor recoil pressure is neglected; and (3) the heat source is modeled by surface heat flux or volumetric heat source. In reality, as the laser beam irradiates the powder layer, it penetrates through the depth of powder bed and undergoes multiple reflections between the powder particles. Therefore, for more accurately predicting the dimension of melt pool, modeling the heat source in FEM simulations for the SLM process is considered as the key issues (Foroozmehr et al., 2016). Accordingly, the authors in (Foroozmehr et al., 2016; Gusarov et al., 2009; Yin et al., 2016) proposed various methods for constructing the volumetric heat source in the SLM process. For example, in (Gusarov et al., 2009), the heat source is related to the absorptivity profile along the depth of powder layer, where this profile is constructed based on the two-dimensional radiation heat transfer equation under the assumption that the powder layer is a homogeneous absorbing and scattering medium. For obtaining a good agreement between the calculated results of the contact width, the powder-consumed band and those from experiments, the authors tried to adjust the laser power in simulation. In (Foroozmehr et al., 2016), a volumetric heat source was constructed by using an optical penetration depth (OPD) parameter to describe the interaction between the laser beam and the metal powder layer. For obtaining a good agreement with the calculated melt pool depths and those attained from experiments, the procedure in calibrating the OPD was proposed. Finally, in (Yin et al., 2016), the authors constructed a moving volumetric heat source in which the laser energy density distribution in the x- and y- axis directions was modeled using Gaussian profiles, while that in the z-axis (i.e., depth) direction was modeled using an exponential decay profile. In general, the assumption in literatures (Foroozmehr et al., 2016; Gusarov et al., 2009; Yin et al., 2016) is all based on that the laser radiations only interact with powder particles during SLM process. The hypothesis of slow consolidation implies that the time for the coalescence of powder particles irradiated by the laser radiation is longer than the time of the laser beam passage. This implication is reasonable because the experimental studies from literature (Klocke and Wagner, 2003) proved that the time for the consolidation of two 100–150 μm particles was in the range from several milliseconds to several tens of milliseconds, while the time of laser beam irradiates on the powder particle was in the range of fraction of milliseconds (Gusarov et al., 2009).

The review of literatures provides many useful insights into the interaction between the laser beam and the powder particles in the SLM process. The results indicate that the size distribution of the powder particles has a strong effect on the deposition of the laser energy in the laser-powder interaction zone. However, none of the existing models for simulating the SLM process take the effects of the powder size distribution into account. Accordingly, the present study proposes a new volumetric heat source model for the SLM process, in which a powder layer with various powder particle sizes is constructed using a modified sequential addition method (Tran et al., 2017) and the absorptivity profile along the depth of the metal powder layer is calculated by means of Monte Carlo ray-tracing simulations. In addition, a method is proposed for calculating the thermal conductivity of the SLM powder bed in the pre-melted condition. The validity of the proposed volumetric heat source and thermal conductivity model is demonstrated by comparing the simulation results for the packing density, thermal conductivity, and total absorptivity of the SLM powder bed with the results presented in the literature. The volumetric heat source is then used in a series of Finite Element simulation in COMSOL Multiphysics® modeling software to examine the contact width between melt pool and substrate, the width of the powder-consumed band, and the stability of single scan melt track in the SLM process, respectively.

2. Simulation model for thermal conductivity of packed powder bed

Theoretically, the metal powder layer in the SLM process comprises a structure of discrete powder particles connected by points. However, in a real SLM process, the connection between neighboring powder particles usually have the form of thin necks rather than single points. Accordingly, the authors in (Gusarov et al., 2003) proposed a model for estimating the effective thermal conductivity of packed powder beds based on three structural parameters, namely the packing density, the average coordination number, and the contact size ratio between neighboring particles. In particular, the effective thermal conductivity was computed as

$$\frac{\lambda_e}{\lambda_s} = \frac{pn}{\pi}x \tag{1}$$

Where λ_e is the effective thermal conductivity of the packed bed, λ_s is the thermal conductivity of the corresponding bulk material, $p$is the packing density of the powder layer, n is the average coordination number (Note that the coordination number is the number of contact points between a particle and all its surrounding particles, and the average coordination number of the powder layer is the sum of the coordination numbers of all the powder particles divided by the total number of particles within the layer), and x is the contact size ratio (defined in (Gusarov et al., 2003)). As shown in Eq. (1), to calculate the effective thermal conductivity of the powder bed, it is first necessary to estimate the thermal conductivity of the solid material and the three structural parameters of the packed bed described above. The method employed in the present study to calculate the effective thermal conductivity of the packed bed is briefly described as follows.

Firstly, the modified powder deposition model proposed by our group in (Tran et al., 2017) was used to construct the SLM powder bed. The simulation process commenced by randomly selecting a particle from a powder package with a pre-defined size distribution. Following its release, the particle was moved through multiple steps along the vertical direction until it attained a stable condition. (Note that full details of the modified sequential addition model are available in (Tran et al., 2017).) Fig. 1(a) shows the typical Matlab simulation results obtained using the proposed deposition model for a metal powder layer with dimensions of 0.5 × 0.5 × 0.2 mm. Fig. 1(b) shows the corresponding powder size distribution.

Having constructed metal powder layer, the packing density and average coordination number were extracted directly from the simulation results. Assuming the use of Stainless Steel 316L powder to construct the powder bed, the thermal conductivity of solid Stainless Steel 316L at room temperature is set as 15 W/mK (Taylor and Howard, 1961) because the experiment conducted in literature (Rombouts et al., 2005) to measure the thermal conductivity of stainless steel 316L powder is at room temperature. Furthermore, by tuning the contact size ratio x in Eq. (1) in the range of $0 < x < 0.3$ (Gusarov et al., 2003), a contact size ratio of 0.0119 was found to be sufficient to calculate the effective thermal conductivity for powder beds with various powder size distributions. Table 1 compares the simulation results obtained for the packing density and effective thermal conductivity of three powder beds with different size range distributions ($d_{10} - d_{50} - d_{90}$) with the experimental results presented in (Rombouts et al., 2005). It is observed that a good agreement is obtained between the two sets of results for each powder bed.

3. Volumetric heat source modeling

The present study also bases on the mentioned assumption and proposes a new, more realistic, method for modeling the volumetric heat source in the SLM process. In the proposed approach, the powder layer (comprising particles with various sizes) is constructed using the modified sequential addition method described in Section 2, and the