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Heat transfer in granular medium for application to selective laser melting: A numerical study

Ram Dayal [a], [*], Tatiana Gambaryan-Roisman [b], [**]

[a] School of Automobile, Mechanical and Mechatronics Engineering, Manipal University Jaipur, Jaipur, India
[b] Institute of Technical Thermodynamics and Center of Smart Interfaces, Technische Universität Darmstadt, Alarich-Weiss-Str. 10, 64287, Germany

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ABSTRACT

In this study, the heat transfer in a granular medium due to a moving laser source is investigated numerically. A numerical model on laser energy absorption and its transport in granular media is presented. This process is especially relevant to laser melting/sintering of metal powders. The non-continuum approach is used to consider the discrete nature of granular medium explicitly. The validation of each of the individual modules of the thermal model is presented. The simulation results demonstrate the ability of numerical approach to predict powder bed properties and influence of laser melting/sintering process variables (grain size, material emissivity, substrate property etc.) on laser energy distribution and transport in the powder bed.

1. Introduction

Selective laser melting (SLM) is a powder based layered manufacturing technology, where the scanning laser beam is used as a heat source to fuse the layers of powder particles. As a type of layered manufacturing it inherits all the advantages associated with it. Among all the layered manufacturing techniques, SLM is one of the most versatile. It is based on localized heating and resulting fusion between the powder particles. In principle, the SLM technology is applicable to any material available in powder form. It is this property of laser melting technology, that makes it an ideal candidate for researching and developing new material systems, especially metals and alloys. In addition, SLM allows for local discontinuity in material, opening up further scope for part tailoring in terms of property and material gradient [1].

The primary building block for laser melted or sintered part is powder grain in a loosely packed powder bed. This packing structure represents the state of the medium before consolidation, and it invariably affects the whole process. The laser assisted melting/sintering is initiated by local heating of powder layer using laser beam. Among various phenomena that occur during the process (e.g. energy absorption, inter-particle heat transfer, coalescence etc.) most of them are either purely thermal or thermally induced. This underlines the need to develop a thermal model, considering the granular nature of medium and selective heating by moving laser source, to improve our understanding of selective laser melting process.

Dedicated heat transfer studies in granular medium for application to laser melting are rare, Gusarov et al. [2]. proposed a model for effective thermal conductivity of powder bed under conditions identical to laser sintering. Gusarov and Kruth [3] used continuous approach to model powder bed and used two flux method to solve radiation transfer equation. This model was further extended to include conduction heat transfer and the diffusion equation is solved by finite difference [4]. Zhang et al. conducted numerical studies on laser melting of metal powders [5–8]. However, they also assumed powder bed as homogeneous medium and modeled effective properties of medium in their investigation. Nevertheless, making an assessment of effective properties is difficult and mostly focussed on mean behaviour of medium with very little or no consideration of local variation. Whereas, in case of laser melting, the heat transfer in the powder bed is extremely localized around the moving laser beam and the assumption of continuum treatment is invalid, since the requirement of local thermal equilibrium [9] is violated. The powder bed does not exhibit homogeneous

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[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: ram.dayal@jaipur.manipal.edu (R. Dayal), gtatiana@ttd.tu-darmstadt.de (T. Gambaryan-Roisman).

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behaviour under these conditions [10].

Our aim in this study is to develop a thermal model for laser energy absorption and its transport in granular media, with specific significance during selective laser sintering of metal powders. The non-continuum approach is adopted, in order to explicitly model the distribution of individual particles in the powder bed (using dynamic packing algorithm [11]) and predict heat transfer in the resulting discrete medium, to be able to predict process window numerically.

2. Modelling

During selective laser Melting, heat transfer to the powder particles due to a scanning laser beam (see Fig. 1) influences the processes following thereafter (e.g. melting, coalescence, solidification). We use the ray-tracing approach to model the absorption and propagation of laser radiation energy in the granular medium. Interparticle thermal radiation and conduction is also considered, while the convection heat transfer is assumed to be negligible [12], since process takes place in stagnant inert atmosphere. Heat transfer in the particles is modeled using lumped mass approximation. Therefore, temperature fields within the particles are assumed to be uniform. It is implied that any particle heated to temperature above its melting point is melted, and the temperature of each particle is evaluated after accounting for the enthalpy of fusion. Under these assumptions, the energy balance for a particle is given as

$$m\frac{dh}{dt} = \dot{Q}_{cond} + \dot{Q}_{rad} + \dot{Q}_{src}, \tag{1}$$

and

$$h = \begin{cases} C_s T & T \le T_m; \\ C_l T + H_f & T > T_m. \end{cases} \tag{2}$$

Where h is specific enthalpy, C_s and C_l are specific heats for solid and liquid states, respectively. The source term, $\dot{Q}_{src}$ accounts for the absorbed laser radiation by each particle. This is modeled using ray-tracing described in next section. $\dot{Q}_{cond}$ and $\dot{Q}_{rad}$ are heat exchange terms due to interparticle conduction and radiation, respectively. The modelling details for each of these terms and solution algorithm are described in following the sections.

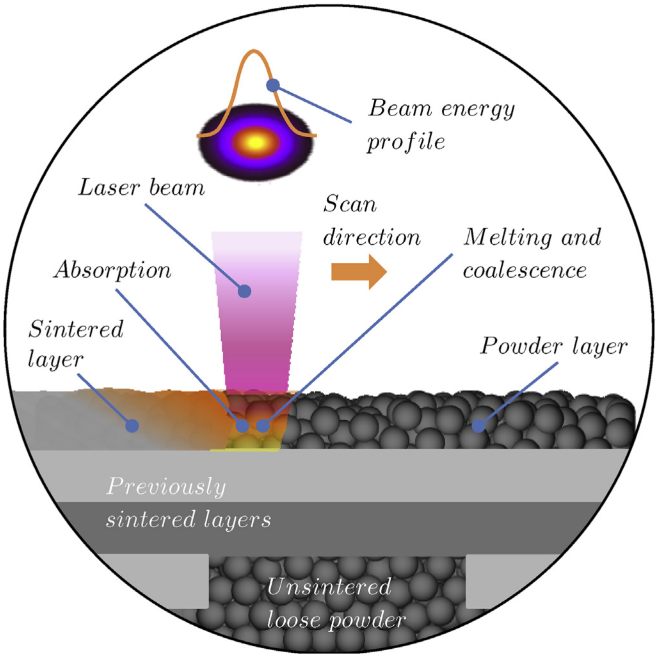

Fig. 1. Schematic of laser sintering showing key phenomena occurring during the process.

2.1. Laser radiation source using ray-tracing

Ray-tracing [13–15] is a simple method to describe light propagation and scattering through a complex medium, under the limiting case of wave optics ($\pi D/\lambda \gg 1$), where D is particle grain diameter and λ is the wavelength of the incident radiation [16]. In ray-tracing method, the laser beam is represented by a large number of individual rays that travel through the medium while all the associated events like ray-surface intersection, energy absorption, reflection, etc. are recorded. The method is independent from coordinate system and does not require any domain discretization. Thus making it ideal for this problem, provided ($\phi_b \gg \lambda$), where ϕ_b is the laser beam diameter. The beam is assumed to be composed of large number of rays (see Fig. 2). The energy of each ray e_i at its origin depends on the beam energy profile and its spatial position in the beam, which is given by

$$e_i = \frac{P_o \Delta t}{N} f(x_i, y_i), \tag{3}$$

where N is the total number of rays used to represent the laser beam, P_o is power of the beam, Δt is time step size and $f(x_i, y_i)$ is the factor to account for spatial distribution of energy in the laser beam. For a Gaussian beam of radius r_b, the distribution factor is given as

$$f(x_i, y_i) = 2 \cdot \exp\left(-2\frac{(x_i - x_c)^2 + (y_i - y_c)^2}{r_b^2}\right), \tag{4}$$

where (x_i, y_i) and (x_c, y_c) are coordinates of ray origin at the source and beam centre respectively. Since the propagation speed of laser radiation is equal to speed of light, the time needed for a ray to be completely absorbed in the powder bed is just a fraction of picosecond. Thus, for every time step, each of these rays is tracked until it imparts all its energy to the interacting medium or it escapes out of the system.

Random numbers are used to generate uniformly distributed origin points. The coordinates of ray origin on a plane circular surface is given by

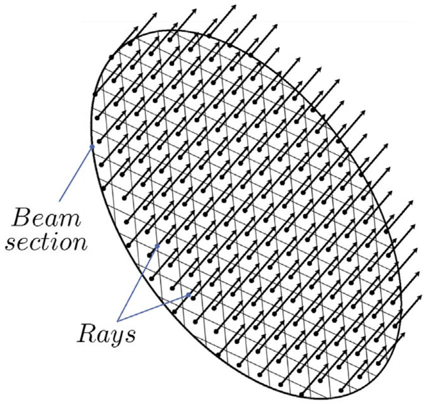

Fig. 2. Laser beam partitioned into rays (Each arrow represents an individual ray).