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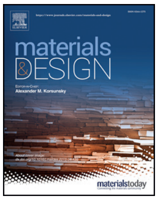

Model of laser energy absorption adjusted to optical measurements with effective use in finite element simulation of selective laser melting

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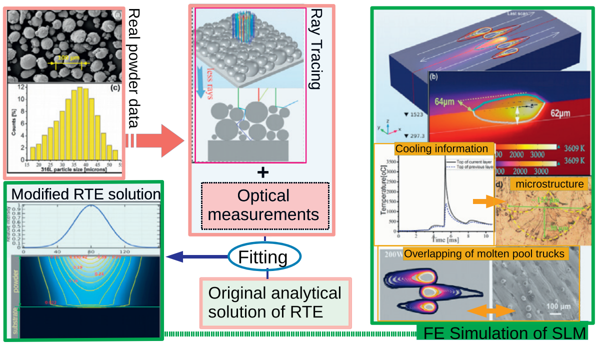
HIGHLIGHTS

- Laser absorption is modeled in a powder-substrate setting with reference to optical measurements
- Diffuse mode gives the best approximation of laser absorption; which agrees with observed particle surface
- Simulation agrees well with observed melt trucks and cooling information interprets well the final microstructure observed.
- For fixed hatch and layer thickness, energy density metric can work locally; if an "off-set power" is introduced

GRAPHICAL ABSTRACT



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ABSTRACT

The presented research work has developed an adjusted analytical equation that can accurately describe energy absorption in powder-substrate geometry observed in Selective Laser Melting. Without high demand of computing capacity, this equation can be used in Finite Element evaluation of temperature profile that explains well experimental observations. The equation was developed from a solution of one-dimensional Radiation Transfer Equation. The adjustment is made referring to measured absorption data extended using a carefully set Ray Tracing model. The diffuse mode of radiation propagation was found to be more accurate for atomized powder. This agrees with observed particle surfaces that are not mirror-like to qualify for specular reflection. Simulated cooling curve helped to understand the influence of scanning a given layer on final microstructure of underlying layers in 316L SS. By studying different combinations of laser power and scanning speed; data for prediction of "under-heated", "well-heated" and "excessively-heated" regions were generated. These data revealed that, in a certain range of laser power, the concept of energy density metric can still work for fixed hatch and layer thickness; if an "off-set power" is introduced.

1. Introduction

Selective Laser Melting (SLM), like many other additive manufacturing (AM) techniques, offers flexibility in design expected to become a disruption to the manufacturing industry [1]. On top of that, SLM can allow a localized control on microstructure leading to synthesis of materials with unique physical properties. SLM simulation is an important tool to explore more possible interesting designs with relatively low cost in terms of time and means. Many SLM simulation models have been proposed; but the granular nature of powder has brought many limitations to the coupling of laser energy absorption models and heat

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transfer in SLM. As demonstrated based on powder consolidation experiment [2, 3], for relatively fast and small laser beam commonly used in SLM today, laser absorption is likely to happen in powder bed before consolidation takes place. In this regard, a powder-substrate configuration is suitable for laser energy deposition modeling. Ray Tracing (RT) method can produce more accurate energy deposition profile [4–7], but in this method every single particle constitutes a separate geometry which increases the degree of freedom (DoF). Fortunately, it takes just a few time-steps for each ray to be almost totally absorbed. Hence, the high DoF is not a big issue in RT itself. Nevertheless, coupling RT to heat transfer numerical models becomes very challenging due to a high number of time-steps required to simulate SLM process. In the framework of Discrete Elements or Volume of Fluid Methods, some researchers have tried to adopt the granular geometry used in RT to simulate SLM [6, 8–12]; but these studies are limited to small domain-sizes in a single scan of one line. This limitation in domain-size, not only increases simulation error, but also implies limitation in the range of application of simulated results in the real world.

Finite Element Methods (FEM) have been widely used by researchers as a good alternative with larger domains and multiple scans [4, 13–22]. Tremendous efforts were made to build efficient models for thermal properties of granular material [23, 24], phase change [25] and mass transfer to be used in FE simulation of SLM. On the other side, there is still divergence about models of laser energy deposition used in FE simulation of SLM. A recent review on SLM Simulation models, demonstrated that the quality of a model for SLM simulation increases with the number of physical parameters taken into consideration [26]. The surface energy flux absorption model, where a Gaussian heat flux is deposited on the top surface, is one of the most adopted in FE simulation of SLM [13–19, 21, 22, 27]; though it ignores powder parameters like particle size, powder packing and powder layer thickness. A more realistic average-medium exponential decay law has also been used [8, 28, 29]. Though an average radiation penetration depth is considered in the model, the importance of particle size, powder packing, and powder layer thickness are not explicitly considered. In addition, the effect of reflection by substrate, multiple reflections in powder, forward and back scattering phenomena are also not captured in both models. Nonetheless, it has been demonstrated that light scattering through air voids dramatically changes the distribution of energy absorption profile [4]. It is also known from optical measurements that total powder absorption is considerably higher compared to corresponding bulk material [30, 31].

Gusarov and Kruth proposed a one-dimensional (1D) analytical solution of the Radiation Transfer Equation (RTE) in a powder-substrate configuration whose approximation is close to RT [32]. This 1D-RTE solution has a unique importance compare to RT: it is an analytical expression that can easily be implemented in FE simulation to describe the powder-substrate nature of SLM. However, to the best of our knowledge, only one research has tried to use the 1D-RTE solution in a FE model of SLM [2]. In addition, comparison with two dimensional (2D) numerical solution of the RTE [33] has shown that the 1D-RTE analytical solution overestimates the axial deposited energy due to radial broadening effect not captured in 1D approximation. This radial broadening refers to a weak radial component of energy density flux that rises when the beam starts to interact with powder; though the incident energy density flux is normal to the surface of powder bed. This tends to lower the energy density in the center of the beam at the expense of energy density tails beyond the beam size. The deviation between the two models becomes even more important for smaller beams; which are the most common in today's SLM machines.

Based on measured optical and geometrical data, we propose an adjustment of 1D-RTE solution in powder-substrate setting to describe laser energy absorption in FE simulation of SLM. For that, we extend experimental data using a carefully set RT model, then use data as a reference gauge to propose correction to the original 1D-RTE model. The use of the modified 1D-RTE model in a FE simulation of SLM is validated using various experimental results with a laser of 40 μm beam radius and 316L SS material. The quality of melting is discussed vis-a-vis the energy density for a large set of simulated combinations of power and scanning speed.

2. Model of laser energy absorption

2.1. Capturing granular and optical information of substrate and powder

Measured optical and granular data of commercial powder and printed parts are the starting brick: surface reflectance of solid phase, total reflectance of the powder bed, particle size distribution, relative density of powder bed and powder layer thickness used in SLM. However, experimental measurements only could not provide enough data for different materials with surface reflectance from 0 to 1. In addition, powder absorption measurement can only be done for deep powder bed and not powder substrate setting. To overcome this limitation, the measured granular data were used to generate deep powder bed geometry and powder-substrate geometry. These geometries and laser beam, in the state-of-experiment, are used in RT simulation to produce absorption data for the whole range of R from 0 to 1.

2.2. Ray tracing simulation

A sufficient number of rays making a Gaussian beam of 40 μm radius are traced. A beam striking under a normal incidence a deep powder bed or a layer of powder on a bulk substrate is considered. In the limit of geometric optics approximation, the size of geometric entities must fulfil certain conditions. It is reasonable to estimate particles of typical powder used in SLM as spheres. The average diameter must fulfil the relation $\pi D / \lambda \gg 1$. For SLM using a laser wavelength $\lambda = 1.07$ μm or beyond, the condition above becomes $D \gg 0.34$ μm; which is well fulfilled for almost all commercially averrable powders designed for SLM. Fig. 1 (a) gives the basic concept of the RT. In this RT, every ray is traced individually using COMSOL Multiphysics commercial software [34]. During ray tracing, reflection on every gas-metal interface and propagation in gas between two consecutive interfaces is explicitly studied for every ray until it is totally absorbed or reflected outside the powder bed. Parameters measured for the SLM machine used in experiment were used to describe the initial TM_{00} mode Gaussian beam. After hitting the powder bed, intensity and polarization of each ray is computed along the path using Stokes parameters. Normally, Stokes vector reinitialization during reflection of s- and p- polarized rays, can be done using Fresnel equations for respective polarizations. However, by “opaque spheres” method assuming negligible penetration depth in metal, the use of measured full reflectance of metal surface can give better accuracy compared to the use of estimated optical index of metal. We adopted this method to calculate the intensity of absorbed and reflected ray at each interface. Ray trajectory can be computed by solving six coupled first-order ordinary differential equations defining time-dependence of the wave vector, position vector and angular frequency. Tracing is ended when a ray reflects by escaping the powder bed or until the relative intensity, compared to initial intensity, falls below a given threshold set to 1/1000 in this work. Detailed mathematical formulation is provided in supplementary material.” Specular and diffuse modes are separately studied. Contrarily to the specular mode, in diffuse mode many forward and back scattering rays immerge from one incident ray, as it is in real situation of a rough surface: due to local surface non-uniformity, two close parallel rays reach the surface at different incidence angles resulting in different reflection angles as illustrated in Fig. 1(b). Powder geometry was prepared according to particle size statistics measured for commercial 316L SLM powder: 15 different average sizes were considered in accordance with measured particle size distribution. A simple code was used to generate coordinates of particle centers so as to realize a powder bed with approximately desired packing density. Stability of the model vis-à-vis the number of rays and position