Materials and Design 143 (2018) 12–19

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Laser energy absorption behavior of powder particles using ray tracing method during selective laser melting additive manufacturing of aluminum alloy

Ying Yang, Dongdong Gu *, Donghua Dai, Chenglong Ma

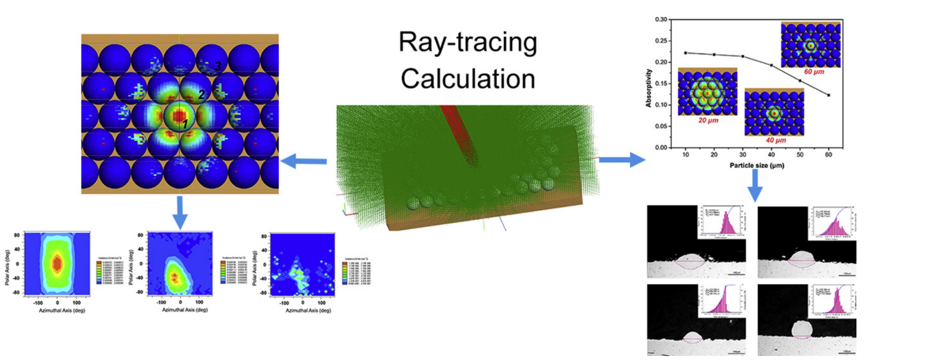
[a] College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing 210016, PR China

[b] Jiangsu Provincial Engineering Laboratory for Laser Additive Manufacturing of High-Performance Metallic Components, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, 210016, Jiangsu Province, PR China

HIGHLIGHTS

- Ray-tracing method was utilized to calculate the interaction of powders and laser in an optical model.
- The influence of powder particle size on the absorption behavior is discussed to optimize irradiation condition.
- Experiments have verified the effects of powder particle size.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 November 2017
Received in revised form 11 January 2018
Accepted 21 January 2018
Available online xxxx

Keywords:
selective laser melting
additive manufacturing
ray tracing method
Fresnel absorptivity
irradiance distribution

ABSTRACT

In this paper, a three-dimensional powder bed model, considering Fresnel absorption of *S* and *P* polarization and multiple reflections, has been reasonably proposed. The coupled interaction of the powder bed particles and laser beam energy, mainly focusing on the laser absorptivity and irradiance distribution on powder particles surface and the influence of particle size distribution on the single track molten pool, during selective laser melting additive manufacturing of AlSi12 material using the ray-tracing calculation have been thoroughly evaluated. The results indicated that the energy absorbed on the powder bed was significantly larger than that on the dense flat material and, the distribution of the irradiance was gradually decreasing from the center to the edge of the interaction region. Meanwhile, the powder bed absorptivity and the irradiance of central powder particle of powder bed were found to be sensitive to the powder particle sizes. The absorptivity of the AlSi12 powder bed decreased from 0.222 to 0.123 for the particle size ranging from 10 μm to 60 μm, respectively. The contour of the irradiance distribution continuously changed from the uniform pattern to the double peak and terminally to the single peak for the increase in the particle size. The influence of the particle size on the cross section of the single-track morphology was experimentally studied, having a good agreement with the results predicted by the simulation.

1. Introduction

Selective Laser Melting (SLM), based on a complete melting/solidification mechanism, as a rapidly developed method of additive

* Corresponding author at: College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing 210016, PR China.
E-mail address: dongdonggu@nuaa.edu.cn (D. Gu).

https://doi.org/10.1016/j.matdes.2018.01.043
0264-1275/

manufacturing (AM) technique, has offered a wide range of advantages as the net-shape fabrication [1–3]. The application of SLM is growing in fields such as aerospace, orthopedics, and dentistry due to its ability to generate complex three dimensional metal parts [4,5].

The capability of powder particles to absorb energy radiation is a dominate premise for the powder bed based additive manufacturing (AM) technologies process. The laser energy absorptivity of the powder material is generally identified as the ratio of the powder material absorbed radiation to the laser energy completely incident radiation. Klassen proposed a model based on a set of semi-empirical equations demonstrating that electron beam absorption and penetration depth had a strong influence on the quality of the fabricated product during electron beam melting (EBM) process [6]. The normal spectral absorption of a number of metal, ceramic and polymer powders susceptible to be utilized for selective laser sintering (SLS) technique was experimentally determined by Nikolay et al. [7]. Their study of the powder absorption is of particular interest for the SLS process development, because it helps to determine the suitable processing window and prior knowledge of powder absorption behavior is necessary to obtain a more uniform and reproducible laser sintering process.

SLM has become a promising process for manufacturing industrial engaging in the fabrication of aluminum parts and aiming to deliver their new customized products more quickly. However, different from copper alloy and nickel alloy with high absorption [7], the high reflectivity of the laser beam, high affinity to the oxygen and the efficient thermal conductivity of aluminum material provide a considerable challenge for the efficient controlling of the process [8–10]. As a result, the investigation and optimal design of absorption behavior of aluminum materials during SLM process are works of significance.

So far, some previous researches conducted through the experiments method of measuring laser absorptivity have been conducted. The method of integrating spheres, based on exponential decay, applied to analyze the relationship and describe the amount of energy absorbed within the preplaced powder during the laser deposition process has been proposed by McVey et al. [11]. Another method of measuring the laser absorptivity is calorimetric measurements, which is a simple calorimetric scheme for direct energy absorptivity measurements. The laser absorptivity for a variety of powder materials (metals, ceramics, metal matrix composites, etc.) with different powder size distributions and powder bed thicknesses was reported by Rubenchik et al. [12]. However, it seems that the experimental trial-and-error method is considerably expensive and time consuming to provide a guideline for the SLM process. Moreover, it cannot be revealed that the mechanism of coupling interaction between the laser beam and powder particles through experimental method in detail. Consequently, the numerical investigation approach is reasonably selected as an alternative to cope with these problems [13]. Laoui el al. has developed a simple analytical ray-tracing model to simulate the energy absorption and penetration in SLS [14]. The radiation transfer equation was solved by Gusarov and Kruth using two-flux method considering the cases of the specularly and diffusely reflecting particles [15]. However, due to the characteristic of slim powder layer for the powder-based SLM process, some coupling simulations above may be not appropriate. Boley et al. performed ray-tracing based simulations of successive Fresnel reflections of S and P polarization within metal powder material and, a novel calculation of the laser absorption was proposed with the metal powders and the composite materials [16–18]. In the present work, we used a modified optical model similar to that of Boley, while the radiation irradiance of powder bed and central powder particle as well as the influence of powder particle size on laser absorption were focused on and which was verified by the experiment result.

In the present work, an optical model using the ray-tracing calculation for the simulation of the coupling process and the attendant energy interaction of the powder bed particles and the laser beam was proposed, considering Fresnel absorption of *S* and *P* polarization and the multiple reflections between the neighboring powder particle surfaces. In order to study optimum laser irradiation conditions of the laser energy absorption behavior, the absorbed irradiance distribution on the particle surface and the resultant powder bed has been presented in this paper. Moreover, the influence of the metal particle size on the absorptivity, irradiance and the coupling mechanism between the incident laser beam and the powder material was elucidated. Furthermore, in order to testify the accuracy of the established model using the ray-tracing method, the three dimensions of the molten pool obtained by the designed experiment were compared with the results predicted by the simulation.

2. Modeling

2.1. Optical radiation theory

During the SLM process, the laser radiation penetrates into the spherical surface of the powder particles, rapidly experiencing the reflection, the transmission and the absorption. According to the principle of the optical propagation, the electromagnetic radiation penetrates into the surface, and the angle between the incident light and the normal line is the incidence angle θ. Radiation reflection (R), transmission (T) and absorption (A) are shown in Fig. 1, which sum up to unity:

$$\mathrm{A} + \mathrm{R} + T = 1 \tag{1}$$

The intensity of the reflected radiation I_r can be expressed as:

$$I_r = rI_0 \tag{2}$$

where r is the reflectivity and I_0 the intensity of the incident radiation. During the interaction, the radiation follows the Beer-Lambert law [19]. The Beer-Lambert relationship can be developed to express the intensity of the transmitted radiation I_{tr} at the penetration length of material surface (Z) as:

$$\mathrm{I}_{tr}(\mathrm{Z}) = \alpha I_0 e^{-z/l} \tag{3}$$

$$l = \lambda/(2\pi n_c) \tag{4}$$

where α is the absorptivity, λ is the wavelength of radiation, l is the absorption length, meaning the distance into a defined material as the intensity of the beam has dropped to 1/e. n_c is the real part of the complex refractive index of a defined material, formulated in the function of the wavelength.

Generally, the metallic powder size is dozens of microns at least, since the absorption length is much smaller than the powder radius,

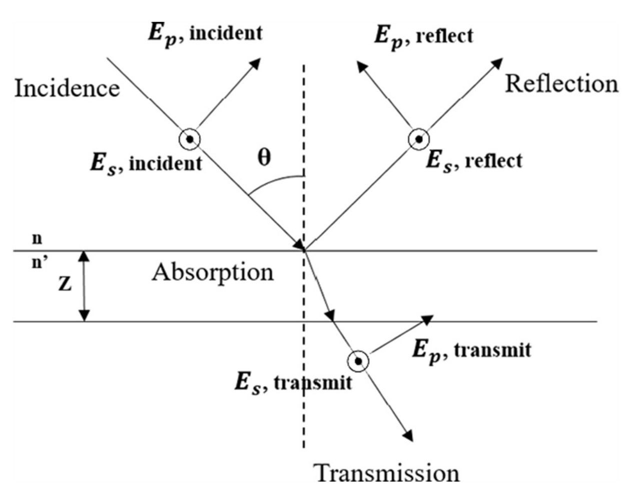


Fig. 1. Schematic of radiation reflection, transmission, absorption and polarization.