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

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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

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.

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1. Introduction

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

\[ A + R + T = 1 \]

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

\[ I_r = rI_0 \]

(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 \( I_t \) at the penetration length of material surface \( Z \) as:

\[ I_t(Z) = \alpha I_0 e^{-z/l} \]

(3)

\[ l = \lambda/(2\pi n_e) \]

(4)

where \( \alpha \) is the absorptivity, \( \lambda \) 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. \( n_e \) 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,
typically of the order of 10 nm–1 µm over the entire range of the laser wavelength of interest [7]. Therefore, the transmitted radiation \( I_t \) can be neglected in the calculation because the radiation transmitted into the spherical surface of powder particles is typically absorbed. As a result, the absorption can be calculated according to Eq. 1: 
\[
A = 1 - R
\]

A polarization of the electromagnetic wave can be generally expressed by the combination of \( S \) polarization and \( P \) polarization. \( S \) polarization means that the electric field is parallel to the incident plane, while \( P \) polarization means that the electric field is vertical to the incident plane (Fig. 1).

### 2.2. Description of optical model

Fresnel formulas give the absorptivity \( \alpha \) of \( S \) polarization and \( P \) polarization at an incident angle \( \theta \) [20], which can be developed as:
\[
\alpha_S = 1 - \frac{(n_c - \frac{1}{\cos \theta})^2}{(n_c + \frac{1}{\cos \theta})^2 + k^2}
\]
\[
\alpha_P = 1 - \frac{(n_c - \cos \theta)^2}{(n_c + \cos \theta)^2 + k^2}
\]
where \( n_c \) is the real part of the complex refractive index and, the \( k \) is the imaginary part of the complex refractive index. In general, a polarization can be expressed as a combination of \( S \) and \( P \) [20].

In the established model, each ray is traced during every interaction and the absorptivity is calculated following the Fresnel formulas. The individual powder particles of the material AlSi12 and the substrate with the material Al were applied in our study. The model is based on some assumptions as followed in our study.

(1) The individual powder particles are ideal spheres.
(2) The powder bed is a hexagonal dense packed arrangement and, the packing style is in the pattern of the body-centered cubic structure (BCC).

An optical source with Gaussian distribution is defined to calculate the interaction of laser beam and the powder particle. The following parameters used in verification of a TEM00 model Gaussian beam are shown in Fig. 2(a).

\[
\tan(\frac{\beta}{2}) = \frac{\alpha_0}{Z_R} = \frac{\lambda}{n_0n_c}
\]
\[
Z_R = \frac{n_0n_c}{\lambda}
\]
where \( \alpha_0 \) is the minimum beam waist, which means the minimum 1/e² semi-aperture in irradiance (1/e in field amplitude) along the beam, \( \beta \) is the far-field divergence angle of the beam, \( Z_R \) is the Rayleigh range, which means the distance at which the beam area has doubled.

\[
\omega(Z) = \omega_0 \sqrt{1 + \left( \frac{Z}{Z_R} \right)^2}
\]
where \( \omega(Z) \) is the beam waist at the \( Z \) distance, which means beam 1/e² semi-aperture in the irradiance (1/e in field amplitude) at a distance \( Z \) from the minimum beam waist.

\[
R(Z) = Z \left( 1 + \left( \frac{R}{Z_R} \right)^2 \right)
\]
\[
\eta(Z) = \frac{\tan^{-1} \left( \frac{Z}{Z_R} \right)}{\tan^{-1} \left( \frac{R}{Z_R} \right)}
\]
where \( R(Z) \) is the wavefront radius of the curvature at a distance \( Z \) from the beam waist and the \( \eta(Z) \) is the phase.

Numerical simulation was performed by using the commercial optical engineering software FRED. A three-dimensional powder bed model using ray-tracing calculation, comprising the laser beam, the densely packed powder particles and the substrate, was established (Fig. 2(b)). The absorptivity (\( \alpha \)) of an isolated substrate, an isolated powder sphere, and the powder bed model were calculated, providing the initial data for the subsequent calculation. The substrate was an aluminum block with the dimensions of 400 × 200 × 50 µm², which was initiated under the powders. The powder particles were defined plenty of the ideal spherical pattern, with the diameter of 30 µm. The TEM00 model Gaussian beam was reasonably defined, with the 1/e² radius of Gaussian beam, the wavelength of the Nd:YAG laser and the input of the laser radiation power of 35 mW, 1.064 µm and 1 W, respectively. The amount of the calculated rays was defined in the order of millions.

### 3. Experimental procedures

A 99.7% purity AlSi12 powder with a spherical shape was selected to obtain four groups of powders with the particle size interval of <25 µm, 25–38 µm, 38–50 µm and 50–50 µm. The powder size distribution of four groups of AlSi12 was measured by a laser diffraction particle size analyser (BT-9300H, China) after filtering. The SLM system consisted of an IPG-500-WC ytterbium fiber laser with a power of ~500 W, a wavelength of 1.064 µm Nd-YAG laser and a spot size of 70 µm (IPG Laser GmbH, Germany), an inert gas protection system and a computer system. Four groups of the powder material with different particle sizes were deposited on four identical aluminum substrates. The processing parameters were remained to be consistent except the powder particle size. The laser power was set to 400 W and, the scan speed was 3000 mm/s, which was optimized by our previous experiment results to have a satisfied effect on the formation of the single track process. The zone of the powder consolidation and the molten pool volume were analyzed.

### 4. Results and discussion

#### 4.1. Fresnel absorption behavior

Fig. 3 shows the calculated \( S \) and \( P \) polarization absorptivity of the wavelength of 1.064 µm light incident on aluminum material at different incident angles using Fresnel formulas. The complex refractive index \( n = 1.03 + 9.25i \), when the wavelength of incident light wavelength is 1.064 µm [21]. It was apparent that the absorptivity for \( S \) polarization had an approximately linear relationship with the applied
incident angle, while the absorptivity for $P$ polarization was slightly increased and then sharply decreased as the incident angle was increased. At the normal incident degree of 0°, the absorptivity for $S$ and $P$ polarization were shown in the same absorptivity with the value of 0.046, For $S$ polarization, the absorptivity was shown in an approximately linear decrease trend for the incident angle increase and the absorptivity was reduced as low as 0 for the incident angle of 90°. For $P$ polarization, the absorptivity was increased to the peak value of 0.2 at the incident degree of 84° while, the absorptivity is sharply decreased to the value of 0 at the incident degree of 90°.

Fig. 4 depicts the complicated interaction of the laser beam and the powder material, the absorption behavior and the multiple energy reflections. Using the ray-tracing calculation, the energy of the individual ray was traced from the laser incident. The complicated interaction of the powder and the laser beam is shown in Fig. 4(a). During the interaction on a spherical surface, the radiation absorption and reflection took place simultaneously while, the energy of the reflected ray dropped due to the Fresnel absorption. When the reflected ray encountered the adjacent particles, another interaction behavior (including the reflection and absorption behavior) occurred. The tracing of the ray was ceased as the ray was reflected into the external protection gas environment, which was regarded as departing the system. Moreover, the trace was typically annihilated as the power of the ray dropped to 0.1% of the original incident power.

Table 1 shows the calculated absorptivity of the isolated aluminum substrate, the isolated powder particle and the powder bed. The absorptivity of Al and AlSi12 of the powder bed model were predicted in the value of 0.160 and 0.214, respectively. It showed that the calculated absorptivity of the powder bed was about double or triple higher than those of the substrate with the value of 0.046 and 0.074 and the isolated powder particle with the value of 0.052 and 0.082, which were caused by the role of the multiple reflections (Fig. 4(b)). The theory of the multiple reflections and the influence of the multiple reflections on the laser absorption have been discussed in several researches [22,23]. Unlike the dense isolated substrates, only a small part of the incident energy was absorbed by the outer surface of the powder bed, most of which was propagated into the inter-particle spaces (gaps) and the interaction was conducted repeatedly between the adjacent powder particles. As a result, the energy efficiency of the powder particles was increased with the generation of the absorption of each ray. The energy absorbed on a flat surface is considerably smaller than on the powder bed, which was confirmed by several studies [7,15].

4.2. Distribution of absorbed irradiance

Fig. 5 illustrates the absorbed irradiance of a combination of the powder bed and the powder particle surface. The irradiance is defined as the radiant energy projected onto the unit area, which is an important physical quantity describing the radiation field characteristics. To explain the absorption mechanism in detail, the irradiance distribution from the top view, as the laser beam radiates vertically on the AlSi12 powder bed, is shown in Fig. 5(a). It seemed that the powder particles near the center region of the laser beam were significantly irradiated. Meanwhile, the irradiance of the powder particle surface was gradually decreased from the center to the edge of the irradiated region and, the powder particles far away from the center region were seldom irradiated.

The absorbed irradiance obtained in the powder particles located from the center of the laser beam to the edge of the irradiated energy region is depicted in Fig. 5(a). The typical three locations, as shown in 1 (center region), 2 (middle region) and 3 (edge region) along the outward radius direction, were selected to study the influence of the radial distance on the absorbed irradiance obtained in the powder material. The contour and distribution of the absorbed irradiance of the powder particle surface are shown in Figs. 5(b), (c) and (d), respectively. It was apparent that the irradiance value decreased from the center to the edge of the irradiated region, due to the distance variation from the laser beam center. Meanwhile, the distribution of the irradiance on the powder particle surface was changing, not only the irradiance value but also the location of the radiated energy. The maximum irradiance value of the powder particle of the position 1, position 2 and position 3 were $0.833 \times 10^{-3}$ W/μm², $0.208 \times 10^{-3}$ W/μm² and $0.002 \times 10^{-3}$ W/μm² respectively. Powder particle of Position 1 not only obtained the radiation from the laser beam directly but also from the adjacent particles, leading to the formation of the highest irradiance (Fig. 5b). The irradiance value of the powder particle located in position 2 was smaller with the generation of the deformed contour. The irradiance contour predicted in the powder particle located in position 3 was in the dispersed pattern, caused by the multiple reflections from the adjacent particles instead of the direct laser beam (Fig. 5c).
4.3. Influence of the powder particle size on irradiated energy

Fig. 6 shows the influence of the different particle sizes, ranging from 10 μm to 60 μm, on the laser energy absorption of the powder particle. It showed that the powder bed absorptivity had a negative relationship with the particle sizes. It was observed that the powder bed absorptivity was 0.222 for the particle size of 10 μm. As the particle sizes increased to 30 μm, the powder bed absorptivity slightly decreased to 0.214. It seemed that the powder bed absorptivity decreased slowly as the particle size was <30 μm. As the particle size increased to 40 μm, the powder bed absorptivity decreased significantly to 0.193. As the particle size further increased to 60 μm, the powder bed absorptivity decreased sharply to 0.123. It was obvious that an increase in the particle size led to more reflection of the laser rays to the external protection gas environment and less penetration of the laser rays to the gaps between the powder particles and, as a result, the powder bed absorptivity declined, indicating the weakened influence of the multiple reflections. When the particle size increased close to laser spot size (70 μm), the reflected rays were seldom attacked to the adjacent particle surface, resulting in the formation of the low energy efficiency. It revealed that the absorptivity was sensitive to the powder particle size. The absorbed irradiance with 20 μm, 40 μm and 60 μm particle sizes was also shown to make a further explanation. The irradiated area of the localized energy deposition getting limited as the powder particle size increased, because of the limitation of the amount of energy radiation obtained in the powder particles, giving rise to the reasonable reduction of the overall absorptivity of powder bed.

Fig. 7 shows the irradiance distribution of the powder material located in the central region of the laser beam for six different powder sizes ranging from 10 μm to 60 μm. The maximum irradiance value of the powder particle for six different powder sizes from 10 μm to 60 μm is shown in Fig. 8. It seemed that as the particle size enhanced from 10 μm to 60 μm, the distribution of the irradiance obtained in the central powder particle surface gradually contracted and, the zone of energy irradiance on the particle surface gradually narrowed. The maximum irradiance also dropped from $1.717 \times 10^{-3}$ W/μm² to $0.745 \times 10^{-3}$ W/μm². When the particle size was small (Fig. 7(a)), the area of the localized energy deposition was homogeneous, indicating the occurrence of the obvious influence of the multiple reflections. It had a tendency to become concentrated when the particle size was 20 μm (Fig. 7(b)), while the two peak value regions of the irradiance occurred on the surface were in the symmetrical pattern. The two peak value regions had a trend of merging into one (Fig. 7(c)), implying the generation of the limited absorption and the attendant high reflection. On increasing the particle size to 40 μm, the area of the localized energy deposition shrunk and focused on the top surface of the powder particle. Finally,
the powder particles with the size of 50 and 60 μm (Figs. 7(d) and (e)) mainly obtained energy radiation from the laser beam. Therefore, the irradiance value was descended because of the decrease of the multiple reflections from the adjacent particles. The weakened role of the multiple reflections brought nonuniformity of the absorption of individual powder particle surface, leading the area shrinkage of energy deposition.

4.4. Experimental verification

Fig. 9 illustrates the cross-sections of the SLM-processed parts obtained on the aluminum substrate, studying the influence of the powder size distribution of AlSi12 material on the SLM-processed single tracks for four different particle size distribution. The mean sizes of the powder particles were 12.08 μm, 30.79 μm, 38.26 μm, and 62.33 μm, respectively. Single track experiments were applied to investigate the influence of the powder particle size on the laser absorptivity. The solidified molten pool boundary, showing the depth and width of the molten pool, was marked in these OM images. The shape of the molten pool was identified to a typically spherical pattern and the molten pool volume was estimated to be [24]:

\[
V_{\text{melt}} \approx \frac{\pi}{6} \times \text{depth} \times \left(\frac{3}{4} \text{width}^2 + \text{depth}^2\right)
\]
Table 2 shows the molten pool size for SLM single tracks using four groups of different particle sizes of the powder material. It was obvious that as the median diameter of the powder particles increased from 12.06 μm to 62.30 μm, the molten pool volume generally shrunk from 0.736 × 10^6 μm^3 to 0.077 × 10^6 μm^3. From the above discussion of the influence of powder particle size on the absorptivity, the powder bed absorptivity was typically improved due to the reduction of particle size. High absorption of the laser radiation gave rise to the enhanced penetration depth, which led to the significant emergence of particle melting. As a result, the molten pool size was large when the particle size distribution is small, promoting the formation of good metallurgical bonding ability.

5. Conclusions

In this paper, an optical model, using ray-tracing calculation for simulating coupling process and energy interaction of powder bed particles and laser beam, was proposed to investigate the laser energy absorption behavior of SLM-processed AlSi12 powder. Several conclusions were drawn as follows.

(1) The incident angle of rays indeed affected the Fresnel absorptivity for S and P polarization. The absorptivity for S polarization had an approximately linear and negative relationship with the incident angle, while the absorptivity for P polarization was slightly increased and then sharply decreased as the incident angle was increased.

(2) The distribution of absorbed irradiance of powder bed and particle surface were analyzed. Powder particles close to the center region were irradiated stronger and the irradiance distribution on the particle surface was concentrated. The role of multiple reflections was found in the irradiance distribution, which had a great effect on the improvement of absorptivity.

(3) The powder bed absorptivity was sensitive to the powder particle size. Small powder particle size resulted in the region of energy irradiance shrinking, both laser beam radiation and multiple reflections considerably promoted the absorptivity.

(4) SLM-processed single tracks experiments were proposed to observe molten pool in cross-section. High absorption of powders with small particle size gave rise to the penetration depth of laser, leading the significant emergence of particle melting.

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Table 2

<table>
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<tr>
<th>Particle size (μm)</th>
<th>D_{50} = 12.06</th>
<th>D_{50} = 30.79</th>
<th>D_{50} = 38.26</th>
<th>D_{50} = 62.30</th>
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<td>Depth (μm)</td>
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<td>V_{melt} (×10^6 μm^3)</td>
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<td>0.495</td>
<td>0.129</td>
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References


