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Laser absorption behavior of randomly packed powder-bed during selective laser melting of SiC and TiB₂ reinforced Al matrix composites

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HIGHLIGHTS:

● A randomly packed powder-bed simulation by sequential addition was proposed.
● The addition of reinforcements enhanced the interactions of laser beam with powder particles.
● The influence of different absorption irradiance on the melt pool dimensions were studied experimentally.

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ABSTRACT

In this paper, a randomly packed powder-bed model by sequential addition method was established mathematically and physically to simulate the condition of the interaction between the laser beam and powder particles. The ray-tracing calculation was used to analyze laser absorptivity and irradiance distribution occurring on powder particle surface as well as the influence of reinforcements on the laser energy absorption during selective laser melting additive manufacturing of pure AlSi10Mg, SiC/AlSi10Mg and TiB₂/AlSi10Mg materials. The simulation results reveal that addition of reinforcements enhanced the interactions of laser beam with powder particles, which were illustrated by an increase of laser ray track spots on the particles surface. A respective absorptivity fluctuated from 0.37 to 0.59 and from 0.34 to 0.49 for the randomly packed SiC/AlSi10Mg and TiB₂/AlSi10Mg, both of which were significantly enhanced with respective to that of AlSi10Mg powder. The addition of ceramic reinforcement particles can significantly improve the absorption irradiance of laser for powder-bed of pure AlSi10Mg, while the SiC reinforcement was more effective in enhancing this effect than TiB₂. The influence of different absorption irradiance on the melt pool dimensions and surface morphologies were studied experimentally to verify the reliability of this simulation.

1. Introduction

Additive manufacturing (AM) refers to shaping layer by layer and consolidation of materials (generally powder materials), using the computer aided design (CAD) model of objective production and high-energy laser controlled by computer. Selective Laser Melting (SLM) technology is regarded as one of the most widespread AM process based on a complete melting/solidification mechanism [1–4], which is taken as one of the most creative manufacturing technologies of the metallic component and provides unlimited possibilities to manufacture components for aerospace, orthopedics, and dentistry [5,6]. SLM has recently become a promising process to manufacture aluminum parts in industry and obtain their new customized products more quickly [7–9]. Various researches on densification, microstructure and mechanical properties of SLM-processed specimens were performed to obtain high-quality components [10–13]. Besides, the absorptivity of the laser beam occurring on the metallic powder is a dominate premise in the optimized of SLM processing, which can improve efficiency in parameter design of SLM processing [14,15]. The laser energy absorptivity of the powder material is generally defined as the ratio of the absorbed radiation of powder material to the incident radiation of laser. Previous researches on the direct measurements of absorptivity were generally conducted by the integrating spheres [16,17] and calorimetric measurements [18]. The absorptivity not only depends on the powder...
material, laser beam size and profile [19], but also is determined by the shapes, size distribution of particles as well as rearrangement of pores [16]. As the laser beam and the melting pool dimensions is in a scale of 50–200 μm in miniature, it is difficult to understand such a complex coupling interaction between the laser beam and powder particles in detail. It is therefore necessary to thoroughly evaluate the optical penetration of the laser beam and the dimensions of miniature molten pool by a numerical investigation approach.

A radiation transfer equation was presented by Gusarov and Kruth when considering the cases of the specular and diffuse reflection of particles [20]. Their study illustrated that the effective radiative properties of powder bed were highly influenced by the reflectivity and the morphology and the size distribution of powder particles. An analytical ray-tracing calculation method has been also proposed by Laoui et al. to evaluate the optical penetration of laser beam and the sintering zone dimensions (thickness/depth and width of a sintered laser track) [21] in order to explore the total energy coupling mechanism. Boley et al. performed simulations of successive Fresnel reflections based on ray-tracing method, which was a novel calculation of the laser absorption using metal powders and composite materials [18,19,22]. Meanwhile, we previously employed an optical model using the ray-tracing simulation to simulate the coupling process and the attendant energy interaction of the powder bed particles with the laser beam [23]. It is found that the laser absorptivity decreases with the increases of powder particle size, which was also verified by the experiment results. Although the powder-bed model by close-packing method was developed, further optimization of the powder-bed model by random packing is still needed to simulate the packing circumstance of actual powder bed. Zhou et al. described a packing algorithm as a numerical method, showing a successive packing of spherical particles in a container with particles dropping one by one in a gravitational field [24]. As their relevant packing parameters and packing pattern in this algorithm were applicable for powder-based additive manufacturing, they were used in this work to efficiently establish the randomly packed powder-bed model.

In the present work, a randomly packed powder-bed model by sequential addition was proposed based on a mathematical method and imported into optical engineering software to perform the ray-tracing calculation. This simulation has considered Fresnel absorption of S and P polarization and the multiple reflections between the neighboring powder particles based on our previous research. To study the influence of reinforcement on the laser energy absorption behavior, laser absorptivity of pure AlSi10Mg and SiC/AlSi10Mg and TiB₂/AlSi10Mg powder-bed along the laser beam path were calculated in this work. The absorbed irradiance distribution on the resultant powder bed and laser ray track spot on the particle surface have been also presented. To testify the accuracy of the laser absorptivity, the surface morphologies and corresponding melt pool dimension obtained by the experiments were compared with those predicted by the simulation.

2. Simulation and experiment
2.1. Description of randomly packed powder-bed model

During the realistic SLM processing, the Gaussian laser energy irradiated into the deposition layers of the loose metallic powder with a nearly spherical shape. In accordance with the actual packing circumstance of powder particles, a randomly packed powder-bed simulation by sequential addition was performed by a mathematical method using MATLAB with a a dimension of 200 × 200 × 50 μm⁢³ in the Cartesian system of coordinates. The size of spherical particles was monosize and the diameter of the spherical particle was 20 μm, as shown in Fig. 1. The colorbar refers to the Z-direction distribution of randomly packed spherical particles. The deposition layer of the loose particles was sequentially built up layer-by-layer, and the top layer was in the most stable state considering their physical properties. The location of each spherical particle was determined by random function with a rule of non-overlap. The spherical particles were restricted by adhesion interaction of contacting ones and the gravity force. When all the spherical particles reached a stable and standstill state, each spherical particle center coordinate (x, y, z) in the simulation was registered.

2.2. Physical ray-tracing method

Multiple complex physical evolutions are involved simultaneously during SLM, including radiation, absorption, melting and solidification, phase transformation, evaporation and thermal conductivity. A schematic of SLM physical model was shown in Fig. 2(a). A ray-tracing method was applied to solve the coupling between the laser beam and powder particles. Fig. 2(b) shows the scheme of multiple interactions of light with a granular layer of spherical particles. In the ray-tracing model, laser rays emitted on the surface of powder particles with a random incidence angle and a certain amount of energy. For each interaction on the particle surface, both radiation absorption and reflection took place simultaneously, while the energy of the reflected ray dropped due to the Fresnel absorption. Partial rays reflected from the powder-bed and went into the external protection gas, while the remaining reflected ray encountered the adjacent particles, leading to another reflection and absorption processes.

The energy of the individual ray was traced starting from the laser
incidence, and the energy absorbed by each powder particle was accumulated in the ray-tracing calculation. The ray-tracing ceased as the ray was completely reflected into the external protection gas environment, which was regarded as departing from the system. The trace was annihilated as the power of the ray dropped to 0.1% of the initial incident power. The electromagnetic wave generally oscillates in more than one direction and can be expressed by the combination of S and P polarizations. Herein, the S and P polarizations refer to the electric field parallel and vertical to the incident plane, respectively. Fresnel formulas were applied to solve calculation of the absorptivity $\alpha$ of S and P polarizations at an incident angle $\theta$, which can be expressed as:

$$\alpha_p = 1 - \frac{(n_e - \frac{1}{\cos \theta})^2 + k^2}{(n_e + \frac{1}{\cos \theta})^2 + k^2}$$

(1)

$$\alpha_s = 1 - \frac{(n_e - \cos \theta)^2 + k^2}{(n_e + \cos \theta)^2 + k^2}$$

(2)

where $n_e$ and $k$ are the real part and the imaginary part of the complex refractive index.

The ray-tracing calculation was performed by a mathematical model, where powder particle layer was imported into an optical engineering software. The optical model consisted of two parts: one was the randomly packed metallic powder-bed and the other was optical
The optical source with Gaussian distribution was defined similarly to our previous study \[21\]. The wavelength was 1.064 $\mu$m, and the model system based on the law that the ray tracing calculation should be used only when the object size of the system model is larger than the wavelength of optics radiation. The \(1/e^2\) radius of the Gaussian beam was 35 $\mu$m, and the Gaussian laser radiation was described in the Cartesian coordinate system as followed:

\[
I(x, y) = \frac{2W}{\pi\omega_0^2} \exp\left(-\frac{2(x^2 + y^2)}{\omega_0^2}\right)
\]

where \(W\) is the laser power, \(\omega_0\) is the \(1/e^2\) radius of the Gaussian beam.

A modified model of a randomly packed powder-bed was established with a three-dimensional dimension of \(200 \times 200 \times 50\ \mu\text{m}^3\), as shown in Fig. 2 (c). Substantial scripts were used to control the laser beam to go along the direction, as the arrow showed in Fig. 2(c). The distance of laser beam path was 200 $\mu$m, which was much larger than the typical sphere size.

![Fig. 4. Ray-tracing calculation: (a) complicated interaction between the randomly packed powder-bed and the laser beam and (b) multiple reflections of the metal matrix composite powder-bed (The red ray represents the incident ray and the green ray represents the reflected ray).](image)

\[\text{Fig. 4. Ray-tracing calculation: (a) complicated interaction between the randomly packed powder-bed and the laser beam and (b) multiple reflections of the metal matrix composite powder-bed (The red ray represents the incident ray and the green ray represents the reflected ray).} \]

\[\text{For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)}\]

2.3. Experimental procedures

2.3.1. Powder preparation

The 99.7% purity AlSi10Mg powder with a spherical shape and an average particle size of 30 $\mu$m and the 99.9% purity SiC and TiB\(_2\) with a near spherical shape and a mean particle size of 3.5 $\mu$m were used. The SiC/AlSi10Mg and TiB\(_2\)/AlSi10Mg composite powder with a reinforcement weight ratio of 10% were homogeneously mixed with a ball-to-powder weight ratio of 1:1, a rotation speed of 200 rpm for 4 h.

2.3.2. SLM processing

The SLM-150 system developed by Nanjing University of Aeronautics and Astronautics (NUAA) consists mainly a YLR-500 ytterbium fiber laser with a maximum laser power of 500 W and a focused laser spot size of 70 $\mu$m (IPG Laser GmbH, Burbach, Germany), an inert argon gas protection system, and automatic powder layering device, and a computer system for processing control. Based on the previous optimization of processing condition, the laser power was set as 350 W and the laser scanning speed was properly settled as 3000 mm/s, in accordance with the parameters used in simulation calculation.

2.3.3. Microstructural characterization

The as-built specimens were cut, ground, and polished according to standard procedures. Then the polished specimens were etched for 15 s with etchant solution consisting of HCl (3 ml), HF (2 ml), HNO\(_3\) (5 ml) and distilled water (190 ml) to reveal the cross-section microstructure of the specimens. To further verify the consistency of the simulation and experiments, the top surface morphologies of the SLM-processed AlSi10Mg and aluminum metal matrix composites were observed by field emission scanning electron microscope (FE-SEM, Hitachi S-4800, Tokyo, Japan).

3. Results and discussion

3.1. Fresnel absorption and reflection behavior

A polarization of the electromagnetic wave can be generally expressed by the combination of S and P polarizations. S and P polarizations mean that the electric field is parallel and vertical to the incident plane, respectively. The calculated absorptivity for S and P polarization versus incident angles of TiB\(_2\) using Fresnel formulas are depicted in Fig. 3. The energy of a photon (\(E\)) can be calculated using the Eq. (4) when Planck constant (\(h\)) is 6.626 × 10\(^{-34}\) J$s$, light speed (c) is 3 × 10\(^8\) m/s, and the wavelength of incident light (\(\lambda\)) is 1.064 $\mu$m.
Refractive indices for TiB$_2$ can be calculated using the relation of energy and momentum of a photon \([25]\).

\[
E = h\nu = \frac{hc}{\lambda}
\]

where \(E\) is the energy of a photon, \(h\) is Planck constant, \(\nu\) is frequency, and \(c\) is light speed.

According to Fresnel formulas, the absorptivity for S polarization and P polarization varied greatly with the change of incident angle \(\theta\). When light reflected along the original path at the normal incident degree of 0°, the absorptivity for S and P polarizations illustrated the same value of 0.403. With the increase of incident angle, the absorptivity of S polarization showed an almost linear trend decreasing to a value of 0 when the incident angle was 90°. In contrast, the absorptivity of S polarization increased to a peak value of 0.82 at an incident angle of 79° and then sharply decreased to a value of 0 at an incident angle of 90°. As the incident light parallel to contact surface at the incident angle of 90°, no interaction happened between the light and surface, leading to no absorption.

Fig. 4 depicts the complicated interaction between the powder-bed and the laser beam obtained using the ray-tracing calculation. The established random packed powder-bed was irradiated by the laser beam, as shown in Fig. 4(a). Millions of original laser rays were set and vertically irradiated into the randomly packed powder-bed with a defined power. The absorption, reflection and transmission happened simultaneously on the metallic powder and the substrate, leading to a decline of the power value. After the first interaction between the particle surface and the laser rays, the reflected rays reached the adjacent particle surface, and proceeded another interaction. This process is called multiple reflections, which play a crucial role in the effect of particles on the laser absorptivity. The transmitted rays either continued to be absorbed by the powder bed or exited the powder bed by reflection, and the portion of the laser beam which that was not reflected and not absorbed was transmitted. Multiple reflections is repeated continually until the laser energy is below the calculated threshold. Therefore for the calculation of this laser ray track, only the

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Fig. 6. Irradiance distribution for the randomly packed powder-bed of pure AlSi10Mg (a); SiC/AlSi10Mg (b); TiB$_2$/AlSi10Mg (c) taken from the top view.
reflectivity and the absorptivity are calculated, and the transmission is ignored. It is not that this part of the energy is ignored, but it is included in the absorptivity or the reflectance. The Fig. 4 (b) shows multiple reflections of the metal matrix composites of randomly packed powder-bed obtained by the ray-tracing calculation. The diameter of reinforcements was 5 μm. It is apparent that the powder particles got a higher laser absorptivity than a block because of the existence of inter-particle spaces (gaps) and the interaction conducted repeatedly between the adjacent powder particles.

3.2. Calculated absorptivity along the laser beam path

Fig. 5 shows calculated laser absorptivity of pure AlSi10Mg, SiC/AlSi10Mg and TiB2/AlSi10Mg powder-bed along the laser beam path, as shown in Fig. 2(c). The laser beam moved from one side to the other side of the powder-bed and we see that local changes in the powder structure caused significant fluctuation in absorptivity. As for the pure AlSi10Mg, the absorptivity ranged from 0.19 to 0.32 with the movement of laser beam at different distances. For the edge positions of the powder-bed model at a scan distance of 0 μm and 180 μm, the lowest absorptivity was achieved because most of the laser rays reflected into the external protection gas environment. Unlike, the incident laser beam could reach a thin powder layer at 40 μm, numerous laser rays penetrated and even reached the substrate, leading to limited multiple reflections and a low absorptivity of 0.25. At 140 μm, the incident laser beam mainly interacted with powder cluster and irradiated into the interspace among the spheres, resulting in more multiple reflections and a maximum absorptivity of 0.32. This increasing absorptivity is ascribed to the shield of laser rays into the substrate and more reflections between powder particles. The laser absorptivity of composite powder-bed is apparently larger than that of the pure AlSi10Mg powder-bed. The SiC/AlSi10Mg and TiB2/AlSi10Mg powder-bed exhibited an absorptivity fluctuation from 0.37 to 0.59 and from 0.34 to 0.49, respectively. As the difference of absorptivity significantly depends on particle size and powder material, the absorptivity variations of the unreinforced alloy and composites can be explained from two aspects. On the one hand, the absorptivity decreases as the particle size of the powder increases [23]. The particle size of the SiC and TiB2 reinforcements (5 μm) is much smaller than that of the metal matrix (20 μm). It is reasonable to expected that addition of reinforcements enhanced the absorptivity of the matrix. On the other hand, although the particle size of TiB2 used in this work is the same as that of SiC, the SiC reinforcement has better absorption capacity than TiB2. It is concluded that The SiC/AlSi10Mg showed the highest absorptivity compared to TiB2/AlSi10Mg and unreinforced alloy.

The lowest absorptivity also occurred in the edge position of the powder-bed model at the distance of 0 μm and 180 μm. The secondly minimum absorptivity corresponded to the step when the laser beam
mainly reached large powder particles. The highest absorptivity happened when the laser beam reached the reinforcement aggregations. The difference in the absorptivity is mainly caused by the distribution of reinforcement and the gathering of small particles offered more possibilities of multiple reflections.

3.3. Absorption irradiance between laser beam and powder

Fig. 6 shows irradiance distribution for the randomly packed powder-bed of pure AlSi10Mg, SiC/AlSi10Mg and TiB₂/AlSi10Mg taken from the top view. The irradiance is defined as the radiant energy projected onto the unit area, which is an important physical quantity to describe the radiation field characteristics. It is apparent that the absorbed irradiance of the SiC/AlSi10Mg and TiB₂/AlSi10Mg powder was higher than that of pure AlSi10Mg. It is because the reinforcements with a small particle size enhanced the multiple reflections from the adjacent particles and thus avoided the numerous laser rays into the bottom metal substrate. This is in accordance with the reported results by Boley [19], where the absorptivity of metal substrate was smaller than powder bed and the absorbed irradiance of aluminum metal matrix composite powder was higher than that of pure AlSi10Mg. Besides, the SiC/AlSi10Mg powder showed a much heavier irradiance than TiB₂/AlSi10Mg powder, which was due to different absorption properties and optical parameters of the reinforcements.

Fig. 7 shows track spot of each laser ray on the particle surface of pure AlSi10Mg, SiC/AlSi10Mg, TiB₂/AlSi10Mg taken from the lateral view. Each track spot of laser ray left on the particles surface after the laser rays was removed, representing the interaction of laser beam with powder particles. Fig. 7(d) illustrates the amount of ray-surface interactions. The number of interactions between the laser rays and particles were counted as $3.41 \times 10^5$ for AlSi10Mg alloy, $3.80 \times 10^5$ for SiC/AlSi10Mg and $4.04 \times 10^5$ for TiB₂/AlSi10Mg, respectively. It was apparent that pure AlSi10Mg powder gained less interactions of laser rays with particles than SiC/AlSi10Mg and TiB₂/AlSi10Mg composite powder. It is supposed that the addition of reinforcements enhances the interactions because numerous laser rays interact with the metal substrate. Besides, the calculated laser absorptivity of SiC/AlSi10Mg powder particles was higher than that of TiB₂/AlSi10Mg powder particles in the same model of randomly packed powder-bed. The higher absorptivity of SiC/AlSi10Mg induced a decreasing power of reflection after every interaction, thus affecting the following reflection behavior. The ray-tracing calculation was annihilated as the power of the ray dropped to 0.1% of the original incident power. As a result, the SiC/AlSi10Mg obtained less interactions between laser rays and particles than TiB₂/AlSi10Mg powder particles.

3.4. Experimental study of the effects of reinforcements on absorption behavior

The morphologies observed from the top surface of SLM-processed pure AlSi10Mg and aluminum metal matrix composites are illustrated in Fig. 8. Appropriate process parameters were applied to present a high-quality surface according to previous studies [26]. The relative density of the AlSi10Mg, TiB₂/AlSi10Mg and SiC/AlSi10Mg samples are 95%, 96.78% and 98.2%, respectively. As the reinforcements were added, the top-surface of SLM-processed specimens exhibited a decreased porosity. It’s worth noting that insufficient melting particles were observed inside some irregular-shaped porosities of pure AlSi10Mg due to relatively low energy was absorbed in the powder system (Fig. 8a). SiC/AlSi10Mg and TiB₂/AlSi10Mg showed limited insufficient melting particles on the top surface because of much higher laser absorptivity during SLM. As the laser energy absorbed by the molten pool increased, further affecting the energy input of the molten pool in the melting behavior, the increasing temperature of liquid phase in the molten pool would improve the wetting behavior of molten pool. The improved wetting behavior between the particles and the matrix would lead to smooth spreading of the liquid phase in the melting process. It is supposed that the metallurgical bond between adjacent scanning tracks was enhanced and the densification was improved, leading to formation of a good surface quality.

The microstructure and the corresponding dimension of melt pool for SLM-processed pure AlSi10Mg and aluminum metal matrix composites are shown in Fig. 9. The cross-section OM images of all SLMed-specimens exhibited a regular and dense feature. It is obvious that the pure AlSi10Mg illustrated a minimum molten pool size, while a
maximum molten pool size was obtained in the SiC/AlSi10Mg. As well seen in the Fig. 9(d), the average width and depth of melt pool were estimated to be 121 μm and 26 μm for pure AlSi10Mg, 191 μm and 63 μm for SiC/AlSi10Mg, and 157 μm and 48 μm for TiB2/AlSi10Mg. Since high absorptivity tended to enhance the operative temperature and accumulated energy within the molten pool due to the sufficient input of laser energy, the viscosity of liquid phase decreased with increasing the operative temperature in the molten pool, which in turn led to better rheological properties of the liquid in conjunction with solid particles [27]. In this case, a large laser energy input induced melted liquid with a long lifespan and a large dynamic velocity accordingly [28]. Conversely, less laser radiation was absorbed, leading to decrease of penetration depth and formation of small molten pool. Therefore, the experimental results verified the simulation about the effects of reinforcements on absorption behavior.

4. Conclusions

In this paper, a randomly packed powder-bed simulation by sequential addition was proposed by the mathematical method and imported into optical engineering software to perform a ray-tracing calculation to investigate the influence of reinforcement on the laser energy absorption behavior. Several conclusions were drawn as follows:

(1) The absorptivity of pure AlSi10Mg powder-bed ranged from 0.19 to 0.32 with the movement of laser beam. With the addition of reinforcements, the laser absorptivity is obviously larger than the powder-bed of pure AlSi10Mg ranging from 0.37 to 0.59 for SiC/AlSi10Mg powder-bed and from 0.34 to 0.49 for TiB2/AlSi10Mg powder-bed. The absorbed irradiance of the SiC/AlSi10Mg and TiB2/AlSi10Mg powder particle surface was higher than that of pure AlSi10Mg.

(2) The addition of reinforcements enhanced the interactions between laser beam and powder particles. The number of interactions were 3.41 × 10^5 for AlSi10Mg alloy, 3.80 × 10^5 for SiC/AlSi10Mg and 4.04 × 10^5 for TiB2/AlSi10Mg, respectively.

(3) The morphologies and corresponding dimension of melt pool of SLM-processed pure AlSi10Mg, SiC/AlSi10Mg and TiB2/AlSi10Mg were characterized and verified the influence of reinforcements on the absorptivity, in good accordance with the results of simulation.

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