Transfer characteristics for laser-induced forward transfer of stainless steel particle

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Abstract. Additive manufacturing (AM) holds great development potential in several applications. In particular, the fabrication of metal parts has been rapidly developing as an industry recently. In such applications, a powder feeder with low material loss is required to ensure effective material usage. Thus, the manufacturing process using laser-induced forward transfer (LIFT) is attractive as a candidate for advances in powder feeder technology. We show that stainless steel particle with diameters of 26 to 53 μm can be transferred via the particle LIFT process; the transfer of particles started at a peak fluence of $\sim$0.05 J cm^{-2} (26- and 36-μm diameters) and $\sim$0.15 J cm^{-2} (53-μm diameter), and the particles were fully transferred (i.e., the probability of transfer reaches unity) at a peak fluence of 0.2 (26 μm), 0.4 (39 μm), and 0.5 J cm^{-2} (53 μm). The initial velocity, v_0, at which the particle leaves the substrate increased proportionally with the increase in peak fluence. When the point of irradiation of the laser beam was displaced from the contact point of the particle on the substrate, the particle was transferred with a transfer angle (i.e., not vertically). These results demonstrate the possibility of transferring metal particles via the LIFT process. To use this technology for AM, the laser power should be adjusted to control the transfer angle of the particle. [DOI: 10.1117/1.OE.61.7.074104]

Keywords: additive manufacturing; powder feeder; laser-induced forward transfer; thermal expansion; stainless steel.

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1 Introduction

Since 1980, the breath of applications of additive manufacturing (AM) has continued to expand. One of the fundamental processes of AM is the powder feeder; one widely used component functioning as a powder feeder is the recoater, which is used to provide powder to the powder bed with a uniform thickness.[1] This component requires that powder is stacked on the powder bed in excess of the required amount and then is smoothed by rollers or blades. The powder feed is an area of AM that has not seen any major innovation since its conception.[2]

Research and development are underway globally, which could contribute to the development of this field. Laser-induced forward transfer (LIFT) technology is an attractive candidate for use as a powder feeder; this process has the potential to replace the recoater.[3] LIFT is a direct-write method allowing for drop-based deposition using a target thin film and a transparent substrate. LIFT technology has been widely studied as a method to fabricate nanometer-scale three-dimensional structures.[4,5] These methods are not applicable to the powder bed fusion method for final parts, where micrometer-scale metal powders are stacked. LIFT technology has also been implemented using flat plate materials rather than thin films. Reports of this method for transferring a flat plate adsorbed on a resin substrate via thermal expansion induced by laser irradiation exist in the literature.[6,7] In this method, the material to be transferred is limited to plate material, which is not suitable for high-speed processing using powder, which is frequently used in the AM field. A LIFT method that uses a target powder on a sacrificial layer has also been

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reported.[8–10] This method utilizes laser absorption of the sacrificial layer, which makes it difficult to reuse the substrates. Laser cleaning (LC) is an established technology in which laser irradiation is used to move a granular material.[11,12] Its principal application is the removal of dust adhering to semiconductor substrates. In this case, the laser is generally irradiated toward the substrate from above. Optical trapping (OT) is also a means of moving powders using a laser.[13–16] In this technique, the powder is attached to the substrate by the van der Waals force and is moved to the desired position using the radiation pressure of incident light.

Recently, a method to directly stack powders using a laser was proposed, and it is regarded as a major innovation in the AM field. Tamura et al.[17] proposed a powder feeder that uses LIFT technology to construct a layer of powder (nylon 12) with an average particle diameter of about 40 μm (a particle size frequently used in AM). This method is able to minimize the amount of powder used in the powder bed and thus reduce powder waste. Sasaki et al.[18] investigated the applications of this method related to resin particles. This method is similar to LC, but it uses a transparent substrate to which the powders are adhered. In this method, if the powder is too heavy, gravity overcomes the adhesion force and the powder is released from the substrate, but the successful adhesion and transfer of powders have been shown for resin powders of up to several tens of millimeters. However, in the LIFT process, if the force applied to the powder is too large, control over the direction of transfer is difficult; in Refs. 17 and 18, the process of powder transfer was not studied. A schematic of these methods is shown in Fig. 1. In the conventional LIFT process, the melting of the material and the sacrificial layer is necessary, and the substrate material cannot be reused. In the LC process, it is difficult to control the stacking direction of powders; thus it is not suitable for applications related to AM. OT requires that each particle is subject to laser irradiation, which has the advantage in terms of accuracy but reduces the possible fabrication speed. In this work, we focus on the particle LIFT method as a means of fabricating objects using powder materials that are commonly used in AM. If the direction of particle transfer could be precisely controlled in the particle LIFT process, new possibilities for metal AM with high productivity will be opened up.

In the particle LIFT process, the particle adheres to the substrate, and the adhesion force is determined by the density and size of the particles. In the literature, there are reports of the LC process being used with ceramics, metals, and polymers, but most such reports focus on particle sizes of 10 μm or less.[11,12,19–23] There are reports of OT processes being used with particle sizes of 2 μm or less.[13–16] The particle LIFT method has been used for polymers with particle diameters of 30 to 40 μm.[17,18] To render such a method applicable to AM, it is necessary to transfer metal powders with a particle size of several tens of millimeters (Fig. 2). This study is an important step toward rendering the particle LIFT process widely applicable. We also discuss the potential for applying this process to metal powder feeders for AM.

For example, to apply the particle LIFT process to AM, it is essential to study the fundamental properties of the transfer process. The transfer probability of a particle from a substrate affects the productivity of the AM process. The speed and the stability of the transfer of the particles are required for the construction of the modeling process, such as the operating speed of the receiving substrate.[17]

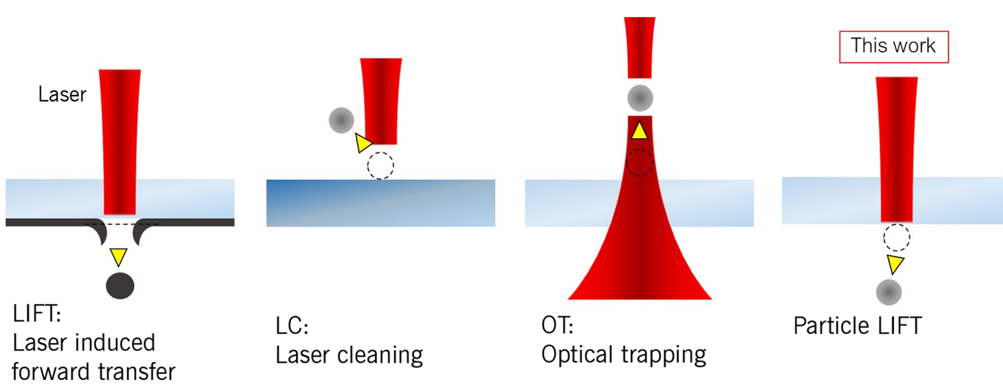

Fig. 1 Powder transfer process. All lasers are downward facing.

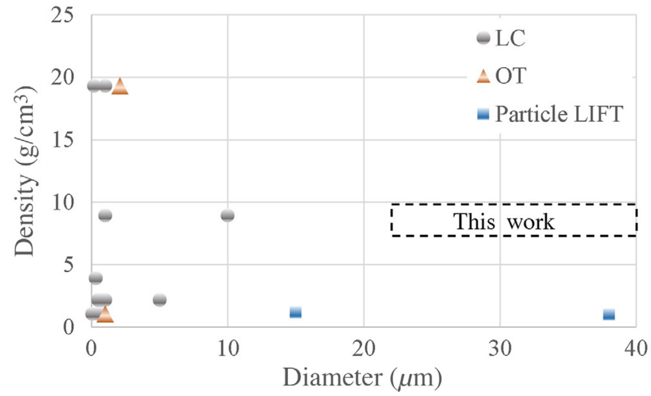

Fig. 2 Mapping of the powder transfer process in terms of particle diameter and material density.

2 Experimental Methods

A schematic of the experimental apparatus is shown in Fig. 3. The laser source used in this work is an Nd:YAG laser with a pulse width of 5.5 ns and a wavelength of 1064 nm. The energy of the laser beam irradiated from the source was adjusted using a polarizing beam splitter and a half-wave plate; the beam was focused on the target material using a convex lens ($f = 150$ mm). The beam diameter was 150 μm (e^{-2}). The substrate used in this work was a sliding glass with a thickness of 1 mm. The target material used in this work was made up of stainless steel microsphere (item code: SSMMS-7.8) particles manufactured by Cospherics Inc.; the particle diameters, here denoted d, were 26, 39, and 53 μm. The peak fluence, F, was calculated from the beam diameter and energy per pulse of the focused laser beam. Laser irradiation was performed in an environment in which only a target particle existed within the beam diameter, and no other particles were transferred via laser irradiation.

A charge-coupled device (CCD) camera (SHODENSHA WA2UVC-500) was used to set the target particle at the focal point, and the transfer of the particle after irradiation was observed from the horizontal direction of the substrate using a high-speed camera (Phantom Miro LC310). The high-speed camera was measured at 64,000 fps, and the timing of the laser emission was used as the reference. The timing of the image capture using the high-speed camera during transfer was performed by synchronizing the camera trigger with the laser pulse.

The CCD camera was used to adjust the laser beam and the particle. The substrate was then moved horizontally to control the x displacement of the irradiation position from the center. Figure 4 shows a schematic indicating how the control of the x displacement was achieved. Figure 5 shows the optical images of the substrate before and after laser irradiation. The particle moved away from the substrate because of laser irradiation at the center of the circle in the figure.

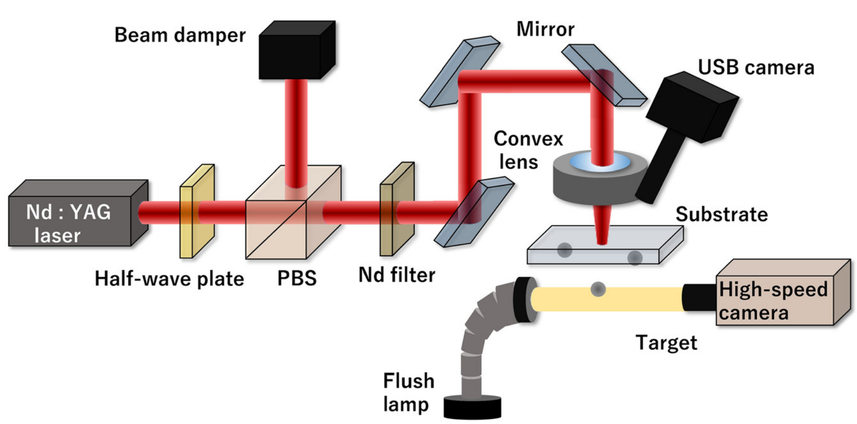

Fig. 3 Schematic of the setup used in this experiment.

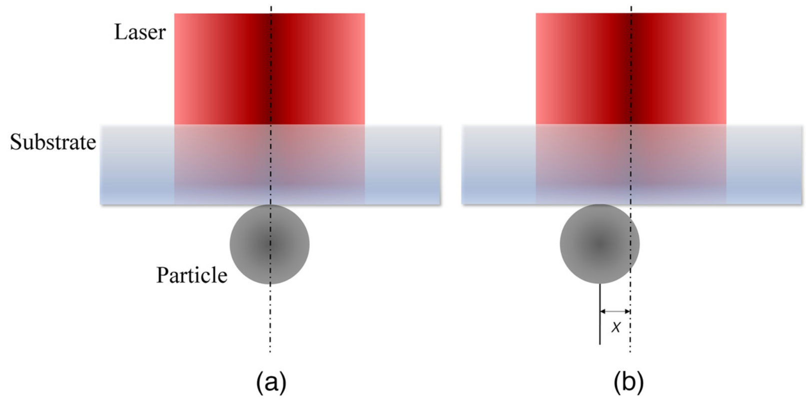

Fig. 4 Schematic of the positioning of the particle in the laser beam. The case of (a) $x = 0$ and (b) $x > 0$.

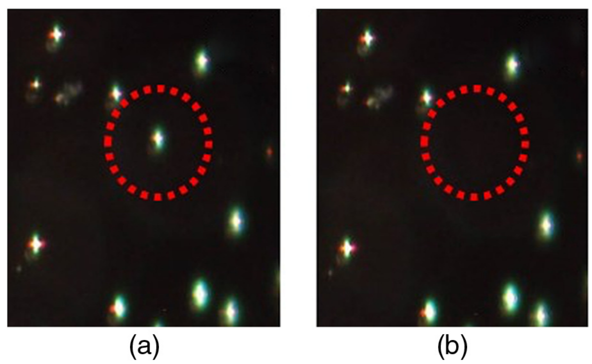

Fig. 5 Optical images of the substrate (a) before and (b) after laser irradiation. Laser is irradiated in the center of the circle.

3 Results and Discussion

Figure 6 shows the transfer probability when a single shot laser is irradiated. The transfer probability is defined as the probability that the particle is detached from the substrate. Transfer probability was calculated using the result of transfer experiments on at least 20 target particles. The laser and the center of the particle were set to be coaxial ($x = 0$ μm). We find that for all

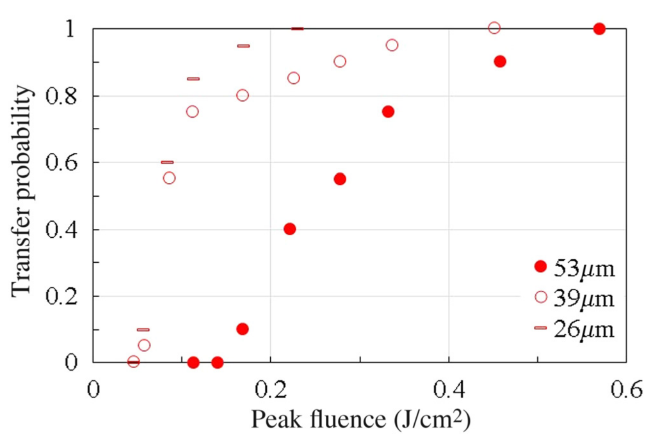

Fig. 6 Dependence of the transfer probability on the peak fluence. The data shown are for particle diameters of 26 (close circle), 39 (open circle), and 53 (dashed) μm.

particle diameters, the transfer probability of the particle can be increased from 0 to 1 by increasing the peak fluence of the laser.

The peak fluence at which the transfer probability was found to be nonzero was 0.05 $\mathrm{J\,cm^{-2}}$ for particles with diameters of 26 and 39 μm and around 0.15 $\mathrm{J\,cm^{-2}}$ in the case of the 53-μm particles. The minimum peak fluences at which the transfer probability for all particle sizes was found to be one were 0.24, 0.46, and 0.57 $\mathrm{J\,cm^{-2}}$ for particles with diameters 26, 39, and 53 μm, respectively.

Alam et al. claimed that the adhesion force between the particle and substrate is due to the van der Waals interactions. The van der Waals force, F_{vdW}, is calculated according to the following expression:[24]

$$F_{\mathrm{vdW}} = \frac{A\,d}{12\,D^2}, \tag{1}$$

where D refers to the distance between surfaces of substrate and particles. In this work, $D =$ 0.2 nm at the largest estimate.[14] A is the Hamaker constant, which is a material-dependent constant; in the case of stainless steel, $A = 21.2 \times 10^{-20}$ J.[25] For the setup considered in this work, the value of F_{vdW} is calculated to be 11.2 μN.

The force of gravity, F_g, acts to favor the detachment of the particle from the substrate. The force of gravity, calculated using the particle diameter d and density ρ, is 0.65 nN. This value is four orders of magnitude smaller than the force due to the van der Waals interaction for a particle 53 μm in diameter. It is expected that the larger the value of d is, the larger the F_{vdW} that will be present is, and thus the larger the fluence required for the particles to be removed from the substrate is.

Here, we show images of the transfer process that were captured by the high-speed camera. Figure 7 shows the images before and after laser irradiation: (a) before laser irradiation; (b) during laser irradiation (0 μs); and (c) 100 μs, (d) 200 μs, (e) 300 μs, and (f) 400 μs after laser irradiation. After the laser irradiation, only the target particles were observed to detach from the substrate in a nonvertical direction.

We define the transfer angle as the angle of the initial velocity of the particle with respect to a straight line directed vertically downward. The initial velocity was calculated from the transfer distance of the particle that occurs in the shortest time unit that can be observed in this experimental setup.

Figure 8 shows the initial velocity, v_0, versus peak fluence, F, when the laser irradiation position coincides with the center of the particle ($x = 0$ μm). For all particle diameters, beyond a threshold of around 2 $\mathrm{J\,cm^{-2}}$, the initial velocity can be seen to increase linearly with peak fluence. The peak fluence intercept obtained by linear fitting in the high peak fluence region is 1.45 $\mathrm{J\,cm^{-2}}$ (for particles with diameters of 26 μm), 1.72 $\mathrm{J\,cm^{-2}}$ (for particles with diameters of 39 μm), and 2.34 $\mathrm{J\,cm^{-2}}$ (for particles with diameters of 53 μm).

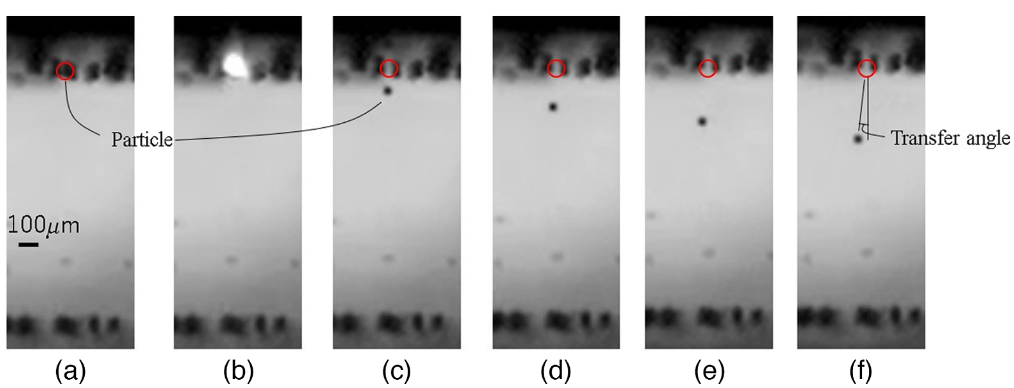

Fig. 7 Side view of a laser irradiating a particle. In this case, the peak fluence is 3.5 $\mathrm{J\,cm^{-2}}$ and $x = 25$ μm. (a) Before the irradiation; (b) at the time of radiation (0 μs); (c) 100 μs, (d) 200 μs, (e) 300 μs, and (f) 400 μs after the irradiation.

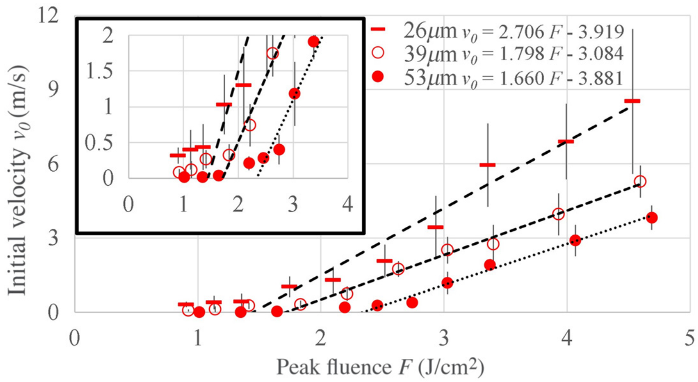

Fig. 8 Dependence of the initial velocity on the peak fluence of the laser.

Sasaki et al. attributed the mechanism that induces the transfer of the particle to the expansion of the particle due to laser beam absorption. The thermal expansion of the particle, Δd, is given by $\Delta d = dK\Delta T$, where ΔT is the temperature increase and K is the linear expansion coefficient of the material from which the particle is made. The temperature rise, ΔT, is proportional to the laser fluence. The initial velocity, v_0, is then given by $v_0 = \Delta d/\tau$, where τ is the timescale associated with the thermal expansion of the particle. The results shown in Fig. 8 indicate that v_0 is proportional to peak fluence, which is consistent with Sasaki's hypothesis of thermal expansion when considering that ΔT is proportional to the laser pulse energy and peak fluence. The transferring phenomenon of a stainless steel particle that we found in this study can be explained via a model in which the particle absorbs the laser beam transmitted through the glass substrate, the laser energy causes the particle to expand, and the expansion of particle becomes an acceleration and detaching force, which transfers away when it exceeds the van der Waals force. At the same peak fluence, the initial velocity tends to decrease with increases in the particle diameter. The laser energy absorbed by the particles increases in proportion to D^2, but the volume of the particles increases in proportion to D^3. Therefore, the temperature increase ΔT of the particles decreases using the particles of large diameters, and the initial velocity shows a tendency to decrease. In this region, the acceleration that depends on v_0 as the detaching force and van der Waals force as the adsorption force are antagonistic, and we believe that we are in a region where particles are transferred very slowly.

Figure 9 shows the value of v_0 and the transfer angle for the particles with a diameter of 53 μm at different fluences and laser irradiation positions. The peak fluence was in the range of 2.5 to 4.5 J cm^{-2}; in this range, the initial velocity is found to be linearly dependent on peak fluence (Fig. 8). When the laser beam was aligned with the center of the particle ($x = 0$ μm), the initial velocity increases with peak fluence, and the transfer angle is almost vertical.

However, for $x \neq 0$, the value of v_0 decreases, and the transfer angle increases; the transfer angle is seen to increase as the irradiation position of the laser is moved closer to the outer edge

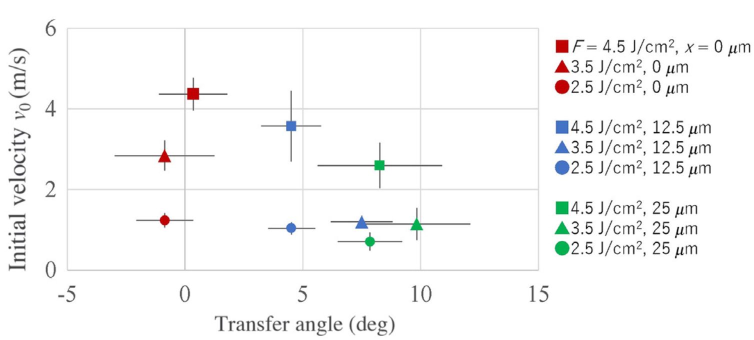

Fig. 9 Transfer angle and initial velocity, v_0, for particles with a diameter of 53 μm, a laser with a peak fluence of between 2.5 and 4.5 J cm^{-2}, and an irradiation position offset of between 0 and 25 μm.

of the particle. The adhesion force, F_{vdW}, acts at the contact surface between the particle and the substrate.[26] Therefore, as x becomes larger, the maximum intensity of the laser beam moves away from the contact surface, and the peak fluence at the contact surface decreases. Therefore, the expansion of the particle along its center line (where the particle is in contact with the substrate) becomes smaller and v_0 also becomes smaller.

Furthermore, because the contact between the substrate and particle is a surface contact, as described in the JKR theory, as x increases, the laser intensity becomes less constant across the contact surface.[26] This is hypothesized to be a factor that causes the slope in the v_0 versus transfer angle curve to appear as x is increased. Transfer angle has a maximum value at the fluence of $3.5\ \mathrm{J/cm^2}$ when x is not 0, but this requires the accumulation of more data.

4 Conclusion

We have shown that a stainless steel particle with diameters from 26 to 53 μm can be transferred via the particle LIFT method using a sliding glass as a substrate. The transfer of particles started at a peak fluence of ~0.05 $\mathrm{J\,cm^{-2}}$ and was complete (the transfer probability is 1.0) at a peak fluence of 0.5 $\mathrm{J\,cm^{-2}}$. The initial velocity, v_0, at which the particle was transferred from the substrate increased proportionally to the increase in peak fluence. This was hypothesized to be due to the thermal expansion of the particle as it absorbed the energy of the laser beam. When the point of irradiation of the laser beam was displaced from the center of the particle, the particle was observed to be transferred in the opposite direction as the direction that the irradiation was displaced from the contact point of the particle on the substrate. It was found that v_0 became smaller as the point of irradiation was moved from the center of the contact point of the particle on the substrate.

These results demonstrate the possibility of transferring metal particles with diameters of several tens of millimeters using the LIFT process and the possibility of using this technology for applications related to AM. To use this technology in AM, it will be necessary to adjust the laser power to control the transfer angle of the particles.

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