Behavior of powder particles on melt pool surfaces

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Abstract

Additive Manufacturing is in progress to change the production and manufacturing environments and possibilities; however, the complex processes taking place are not completely understood yet. A better understanding of the incorporation mechanism of the particles into the melt pool during blown powder processes could lead to methods to increase the powder and energy efficiency. Therefore, the incorporation mechanism was investigated in experiments and simulation. High-speed images made it possible to observe the behavior of single particles on the melt pool. A model based on the temperature-dependent surface tension/energy difference between the particle and the melt pool calculated the time until particle incorporation. It was shown that the surface tension characteristics during particle heating can even lift the particle from the melt pool. The calculated wetting behavior in combination with high kinetic energies should lead to an immediate immersion of the particle into the melt pool. Since observations do not show this behavior, it is concluded that the surface tension plays a role in the incorporation mechanism, but other effects like the occurrence of oxide layers or additional particle heating by the laser beam seem to lead to different mechanisms and heat conductions to support an earlier incorporation.

Keywords Laser additive manufacturing · Powder particle · Surface tension · Direct metal deposition

1 Introduction

Building structures from wire or powder material for creating [1] or repairing [2] industrial parts are the main driving forces and applications of Additive Manufacturing in production. The use of wire or powder material makes it possible to create the desired geometries without wasting much material compared to subtractive machining. Thereby, the production of parts from expensive base materials or bigger structures becomes more attractive. In addition, complex geometries can be realized [3], like overhangs to build, e.g., light-weight designs [4].

Additive Manufacturing processes are based on the accumulation of applied material and usually melting to form the desired geometry of a new part. The additional material is usually applied as wire or powder.

Powder application is realized either by pre-placing the powder in a powder bed (SLM, Selective Laser Melting; LMD, Laser Metal Fusion; Powder Bed Fusion) or by

depositing blown powder to the processing zone (DMD, Direct Metal Deposition; DLD, Direct Laser Deposition; LMD, Laser Metal Deposition) to build tracks and layers to form a structure.

Direct Metal Deposition (DMD) of powder material utilizes a heat source, e.g., a laser beam, to heat the base material and mainly melt the deposited material. Powder particles can be applied by a powder nozzle directed in leading or trailing position [5], while modern powder nozzles use coaxial designs (e.g., [3]). Coaxial nozzles enable a direction independent and highly focused powder application into the processing zone. The laser beam can be either positioned in the center, while the powder is applied around the laser beam or by leading the powder through a central nozzle, while the laser beam is lead around (e.g., [6]). Depending on the application direction of the powder particles, their heating conditions can vary, since they spend different times inside the laser beam, e.g., Han et al. [7] found that the shadow of the particle cloud significantly influences the melt pool shape. Therefore, the incorporation mechanism is important to understand to make the process more efficient in order not to waste powder material.

Different observations were made about the condition of the applied powder. Peyre et al. [8] calculated in their analytical model that no particle melting should take place, while Pinkerton et al. [9] found that powder particles can be heated

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to reach almost melting temperature when applied through a coaxial nozzle. The model from Qi & Mazumder [10] showed that the particles heat up to melting temperature within 10^{-4} s after arriving on the melt pool. Partes [11] could show that melting of the particle surface is possible when they show low melting temperature, low heat conduction, and a good laser beam absorption.

In addition, Jouvard et al. [12] calculated the heating of the powder particles and concluded that the cladding processes need a molten pool to be able to work. This effect was recently confirmed, since the interaction time between liquid particles and the solid substrate in regularly used setups would be too short to ensure the heat transfer from the particle to the substrate for solidification [13].

Depending on the condition of the powder particles when arriving on the melt pool surface, different aspects can define their incorporation:

- Heating of the particles can take place when irradiated by the laser beam and by thermal radiation from the processing zone, which should support the incorporation.
- Particle sizes define the kinetic energy and the energy needed for complete melting [14].
- The kinetic energy of the particle can influence the incorporation [14].
- Surface-tension-driven wetting mechanisms can occur [14].

It was shown in [15] that the particle kinetic energy seems to have a minor impact on the powder particle incorporation. All observed particles that arrived on the melt pool remained part of the track, independently from their speed; however, the particle behavior concerning incorporation duration varied depending on their landing zone.

The different observations about the particle temperatures in literature seem to be reasonable since the particles can take different paths to the processing zone experiencing different heating cycles. When using coaxial nozzles, the particles are not supposed to pass through the high intense areas of the laser beam before arriving on the melt pool. Therefore, it can be assumed that mainly non-melted powder particles arrive on the melt pool surface.

Then, wetting mechanisms of the melt and the particles can occur. The main role during the wetting process plays the surface tension (liquid part) and surface energy (solid part) of the components. Wetting is a mechanism that involves the liquid (l), solid (s), and the surrounding gaseous (g) component. The wetting angle can be described considering the related surface energy σ_{sg} , surface tension σ_{lg} , and interfacial energy σ_{ls} (Young-equation)

$$\cos(\theta) = \frac{\sigma_{sg} - \sigma_{ls}}{\sigma_{lg}}. \quad (1)$$

The surface tension between a solid or a liquid material is given in comparison to the surrounding gas. It is well-known that the surface tension is temperature (T) dependent, e.g., Keene [16] summarized the surface tension σ values and thermal dependencies

$$\sigma(T) = \sigma_{melt} - \frac{d\sigma}{dT} \cdot (T - T_m) \quad (2)$$

with the melting temperature T_m , the material-dependent surface tension at melting temperature σ_{melt} , and the surface tension gradient $\frac{d\sigma}{dT}$.

The equivalent value for solid materials is usually named surface energy and is also temperature-dependent [17]. The surface tension between a solid and a liquid is called interfacial energy, which can be derived from Eq. 1, when the wetting angle was measured in experiments (e.g., [16]).

The extent, to which the final state of spreading can be reached depends also on the viscosity of the liquid and the time until solidification [18]. In powder application processes, the energy transfer direction is from the melt pool to the particle. Therefore, the particle heating will increase its temperature and depending on the thermal conditions even melt the particle.

Due to the high temperatures in the processing zone and the fast process effects, the possibilities of observations of the particle incorporation are difficult. High-speed imaging was used to observe characteristics of the particle interaction with the melt pool (e.g., [15]). These observations showed that all particles arriving on the melt pool are either incorporated when landing in the hot areas around the laser beam or remain on the track after solidification. Immediate incorporation was detected when powder particles land in the vicinity of the laser irradiation and was measured to 0.05 ms. In the surrounding melt pool zone, the particles float in average 0.125 ms until they incorporate.

The powder incorporation is the main mechanism that defines the powder particle usage efficiency and thereby the cost and environmental impact when building an additive part. In addition, the track geometry depends on the powder particle input. A better understanding of the powder particle behavior can lead to more efficient ways and possibilities to control the blown powder processes. In this paper, the incorporation process is further evaluated to identify the main driving forces that define the incorporation of powder particles into the melt pool. It is suggested that the incorporation is based on the wetting mechanism resulting from the difference of surface tensions due to temperature differences.

2 Methodology

2.1 Setup and materials

For the experiments, the setup visualized in Fig. 1 was used.

A continuous wave laser illumination (IPG Photonics, wavelength 1070 nm) of 1.5-kW output power and 3-m/min processing speed was used. Powder particles were applied using a coaxial nozzle (COAX14, Fraunhofer IWS) at a transport gas flow rate of 5 l/min and a powder feed rate of 8 g/min. Argon was used as transport and shielding gas. The powder focus was positioned on the material surface, while the laser beam was defocused 20 mm below the surface resulting in a spot diameter of 2.8 mm on the material surface. Powder and base material were 316L stainless steel. Powder size distribution of the chosen powder was from 50 to 100 μm . A high-speed camera (Photron Fastcam mini UX 100) and an illumination laser (Cavitar cw diode laser) were positioned to observe the particle interaction with the melt pool.

2.2 High-speed imaging

High-speed imaging was done at a recording frequency of 12.500 Hz. Video sequences were evaluated to derive the powder particle behavior when interacting with the melt pool surface (Fig. 2).

The outline of the melt pool was identified in the high-speed videos by determining the moving surface transition to the solid material. Landing zones were defined depending on the observation of the typical behavior of the powder particles. Therefore, the time of particles floating on the melt pool was measured depending on their landing zone (Zones 1 to 4 in Fig. 2). Figure 3 shows the tracking of single particles and their movements on the melt pool.

Only particles that incorporated into the melt pool were considered. In addition, the average particle speeds of the

observed particles were measured by considering the distance of its movement from one frame to the following in combination with the recording frequency until incorporation.

2.3 Incorporation modeling

The aim of the modeling was the derivation of the particle floating duration until reaching the melt pool temperature. This condition was used as the indicator for incorporation, since the surface tension difference is still present.

Since two components (particle and melt pool) with different surface tension/energy due to their different temperatures interact, it can be assumed that wetting occurs according to Eq. 1. Figure 4 illustrates the possible behaviors of a particle when interacting with the melt pool. Depending on the material temperatures, different wetting angles can be expected leading to different heights h of the particle inside the melt pool.

The developed model calculated the wetting angle according to Eq. 1 depending on the actual surface tension values at different temperatures of the particle and the melt pool. Table 1 lists the used values of the surface tension components for modeling. Since the thermal surface tension coefficient is negative, the surface tension decreases with increasing temperature.

Three modeling methods were used: static and temporal with and without particle movement.

The assumed particle diameter d_{part} was chosen to 75 μm as the average of the used powder spectrum. Assuming spherical particles with the density ρ , the mass of a particle is

$$m = \rho \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{d_{part}}{2} \right)^3 \quad (3)$$

2.3.1 Static model

For the static model, it is assumed that the particles rest on the melt pool where they landed. Due to the large size of the melt pool compared to the size of the particle, the melt pool temperature was assumed to remain constant for the calculation. The wetting angle and the particle height in the melt pool were calculated from the initial surface tension/energy values according to Eq. 1. The heat E that needs to be transferred from the melt pool to the particle for reaching melt pool temperature was then calculated at the assumed constant height of the particle in the melt pool following

$$E = c_p \cdot m \cdot (T_{base} - T_{part}) + m \cdot L_m \quad (4)$$

including the base metal melt pool temperature T_{base} , the particle temperature T_{part} , the heat capacity c_p , the mass m , and the energy need for melting using the latent heat of melting L_m .

Fig. 1 Principle sketch of the experimental setup

Fig. 2 High-speed imaging frame showing floating powder particles on the melt pool surface and the defined landing zones

Melt pool outline Zone border markings

The time until the powder particle reaches the melt pool temperature was calculated. Reaching this stage, the surface tension values are the same for the particle and the melt pool, and the particle is assumed to incorporate. The contact angle α was derived using Eq. 1. The height h of the particle inside the melt pool (Fig. 4) is

$$h = d_{part} \left(1 - \frac{\alpha}{180^\circ} \right). \quad (5)$$

The particle surface area A that is in contact with the melt pool is then

$$A = \pi \cdot d_{part} \cdot h. \quad (6)$$

The time until the particle is completely molten is

$$t_{melt} = \frac{E}{A \cdot (T_{base} - T_{part}) \cdot Q} \quad (7)$$

with the heat flow

$$Q = c_p \cdot m \cdot (T_{base} - T_{part}) + m \cdot L_m \quad (8)$$

with the specific heat capacity c_p .

2.3.2 Temporal model (no particle movement)

In addition to the static modeling, the temporal model considers the change of the surface tension of the particle during its temperature increase due to its heating by the melt pool. The melt pool temperature is still considered constant during the calculation. Depending on the actual particle temperature, the surface tension value was recalculated in every time step and the new height in the melt pool was defined after each time step. For the modeling, the time until incorporation was defined as the time that it takes for transferring enough energy

Fig. 3 Sequence of high-speed images for tracking single particles

Fig. 4 Possible wetting situations (left: $>90^\circ$, right: $<90^\circ$ wetting angle) of a powder particle on a melt pool and geometrical measures (evaluated for the case $>90^\circ$)

from the melt pool to the powder particle that the particle is molten (Eq. 4).

2.3.3 Temporal model (including particle movement)

This temporal model expands the previous temporal model considering the observed particle movement on the melt pool before incorporation. The experimentally measured particle speeds were taken to estimate the relative temperature increase of the melt pool that the particle experiences during its movement towards the laser beam. In the center of the melt pool, boiling temperature T_b was assumed, which is in agreement with literature that identified keyhole occurrence during DMD processes (e.g., [20]).

In the model, the particle movement is considered by increasing the melt pool temperature. The temperature of the assumed round melt pool (radius r) at its edge is assumed to be melting temperature T_m (Fig. 5).

Fig. 5 Melt pool assumptions for temperature calculation

The local temperature $T_{melt\ pool}$ at a certain radius x starting at the edge of the melt pool was assumed to be linearly increasing from the melt pool edge to the melt pool center to describe the influence of a changing temperature of the melt pool on the particle heating and is calculated to

$$T_{melt\ pool} = \frac{(T_b - T_m)}{r} \cdot x + T_m \quad (9)$$

including the melting T_m and boiling T_b temperature of the material. The temperature increase along the x -axis (Fig. 5) is therefore

$$T_{grad} = \frac{(T_b - T_m)}{r} \quad (10)$$

Considering the speed of the particle v derived from the high-speed imaging evaluation, the melt pool temperature that the particle experiences T_{incr} is

$$T_{incr} = T_{grad} \cdot v \quad (11)$$

When the particle moves on the melt pool towards the melt pool center, the melt pool temperature that the particle experiences changes based on the temperature gradient.

The duration until incorporation is defined as before. The values that were used for modeling are summarized in Table 2.

MatLab (R2017a) was used to implement the equations and conduct the simulation. The height in the melt pool and

Table 1 Surface tension/energy values

Material	Surface tension/energy in mN/m	Thermal surface tension coefficient in mN/(m ² *K)	Reference
Fe (liquid)	1909	−0.52	[16]
Fe (solid)	2500	−0.455	[17]
Interfacial	200	—	[19]

Table 2 Modeling parameters

Parameter	Symbol	Value
Time step size		$10e^{-5}$ s
Particle diameter	d_{part}	75 μm
Material density	ρ	7874 kg/m ³
Latent heat of melting	L_m	0.268 J/kg
Heat capacity [21]	c_p	444 J/(kg $\times$ K)
Melting temperature [21]	T_m	1538 $^{\circ}\text{C}$
Boiling temperature [21-Bra92]	T_b	2861 $^{\circ}\text{C}$
Heat flow [22]	Q	25,000 W/(m ² $\times$ K)

the duration until incorporation were evaluated at different initial particle and melt pool temperature combinations.

3 Results

3.1 Particle observation

The high-speed-imaging observation showed that the particles that land on the melt pool are made part of the track. Different landing zones as described in [15] were also observed in this work. Particles that land close enough to the laser beam can incorporate, while particles further away can remain on the surface of the track. It was observed that the particles that incorporate later, mainly move towards the laser beam before incorporation (e.g., [15]).

The duration until incorporation of the particles and the related particle speeds were measured depending on their landing zone (Fig. 6). The particle speeds and incorporation durations are the lowest in the central zone (zone 1). The incorporation time increases the further away the particle lands on the melt pool.

Fig. 6 Time duration from particle landing on the melt pool until its incorporation and average particle speed depending on the landing zone

Table 3 Temperature increase depending on the landing zone of the particle

In K/ms	Zone 1	Zone 2	Zone 3	Zone 4
T_{incr}	49	120	102	106

The measured average temperature increase per time due to the particle movement on the melt pool depending on the landing zone is summarized in Table 3.

3.2 Static particle interaction calculation

The calculation of the static model revealed the time from particle landing on the melt pool until incorporation at assumed no particle movement on the melt pool and no height change during heating by the melt pool (Fig. 7).

The initial wetting angles and derived heights of the particle inside the melt pool are shown in Fig. 8.

The calculation considers the latent heat of melting. Therefore, there is a slight non-linearity at particle temperatures around the melting temperature of 1500 $^{\circ}\text{C}$.

3.3 Temporal particle interaction calculation

The particle heating duration was calculated until the particle reaches the melt pool temperature at different initial particle temperatures and melt pool temperatures (Appendix, Fig. 13).

The temporal model without particle movement calculated the height change of the particle in the melt pool as visualized in Fig. 9.

The simulation shows that initially, a complete immersion of the particle is calculated for most calculated cases at high melt pool temperatures, while during the heating of the

Fig. 7 Static calculation of the time duration from particle landing on the melt pool surface until incorporation at different particle and melt pool temperatures

Fig. 8 Static calculation of **a** the wetting angle and **b** the height of the particle in the melt pool at different particle and melt pool temperatures

particle, the particle lifts out of the melt pool again until reaching the melt pool temperature.

Fig. 9 Temporal development of the particle height inside the melt pool of a particle arriving with **a** 100 °C and **b** 1300 °C initial temperature at different melt pool temperatures

When considering the particle movement on the melt pool and the related relative melt pool temperature increase, the incorporation durations become slightly longer (Appendix, Fig. 14), while the particle height inside the melt pool is lower at the end of the calculation at incorporation, which means that the particles stick out of the melt pool even more (Fig. 10).

The edges in the curves occur due to the different temperature increases of particle and melt pool when the particle melts.

The calculated incorporation durations derived from the temporal models are visualized in Fig. 11.

4 Discussion

The complex mechanism of the incorporation of powder particles into the melt pool was investigated. Due to the observed nature of the effect, it is suggested that the surface tension-driven wetting mechanism can be an influencing factor on the incorporation mechanism.

When comparing the theoretically determined and experimentally measured particle floating duration on the melt pool until incorporation, it can be seen that the time in the calculation is slightly overestimated by the temporal model. Reasons might be the additional heating of the particles by the laser beam in the experiments, which was not considered in the model or the chosen stop condition, which defines the incorporation time. Perhaps the

Fig. 10 Temporal development of the particle height inside the melt pool of a particle arriving with **a** 100 °C and **b** 1300 °C initial temperature at different melt pool temperatures

Fig. 11 Time until reaching melt pool temperature of particles with different initial temperatures calculated without and with considering melt pool temperature increase due to particle movement on the melt pool

incorporation can take place at temperatures that are even lower than the melt pool temperature as assumed for the modeling. It could be that the particle incorporates earlier than assumed in the calculation, when both components are liquid; however, the measured incorporation times are similar to the ones presented, e.g., by Qi & Mazumder [10], who calculated the incorporation time to 10^{-4} s (100 μ m steel particle).

Fig. 12 Particle behavior at different temperatures of the particle and melt pool

pool during its heating (Fig. 12). This complete immersion of the particles was not observed in the experiments. It can be assumed that an additional mechanism takes place that keeps the particles floating on the melt pool. In addition, the kinetic energy could support the particle immersion due to the additional resulting force and the closing of the melt pool above it. It could be that a film, e.g., from an oxide layer on the surface could provide the immersion.

Since the particle floats on the melt pool and does not immerse completely as calculated, the effective area used for heat transfer should be even smaller than calculated in most observed cases in this work. Therefore, the incorporation time should be even longer. Since this was not observed in the experiments, it can be assumed that the earlier mentioned effect of an incorporation before reaching the melt pool temperature is most likely.

The observations and calculations show similar tendencies and dimensions. Therefore, the surface tension difference of the melt pool and the particle can be one of the reasons for the observed floating of the particles on the melt pool before incorporation; however, there must be other effects occurring that prevent the particle to incorporate immediately after landing as calculated by the presented surface tension–based model.

5 Conclusions

The comparison of calculated and experimentally measured time durations of particles from melt pool landing until incorporation reveals similar dimensions of the values. It can be assumed that the surface tension effect is one of the driving forces for the floating effect of the particle on the liquid melt pool.

The incorporation of a particle is faster at small differences of the temperatures of the particle and the melt pool and when the particle temperature is above the melt pool temperature.

However, the immersion of the particle into the melt pool is overestimated by the surface tension–based model compared to the experimental observations. Therefore, it is assumed that other effects like the impact of the oxide layer and additional particle heating by the laser beam prevent the particle from incorporation but lead to faster heating and melting.

It was shown that the surface tension–driven wetting mechanism can lead to a lifting of the particle from the melt pool due to temperature differences.

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Appendix

Fig. 13 Calculation of the temporal development of the particle temperature inside the melt pool *neglecting* the particle movement on the melt pool of a particle arriving with **a** 100 °C and **b** 1300 °C initial temperature at different melt pool temperatures

Fig. 14 Temporal development of the particle temperature inside the melt pool *including* the particle movement on the melt pool of a particle arriving with **a** 100 °C and **b** 1300 °C initial temperature at different melt pool temperatures

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