Vacuum laser powder bed fusion—track consolidation, powder denudation, and future potential

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Abstract

Defects in parts processed by laser powder bed fusion (LPBF) are often triggered by laser/plasma plume interference and spattering. The implementation of a LPBF process in vacuum has been suggested to possibly reduce these effects. Within this study, the effects of process pressure variations between 1 mbar and atmospheric pressure on the generation of single tracks and on the surrounding layer of loose powder particles were studied for CP titanium grade 2 and the Maraging steel 1.2709. Below 10 mbar no single tracks could be generated and the powder layer adjacent to the track was effectively denuded. It was found that the essential mechanism for incorporating powder into the melt pool begins to work at process pressures above 10 mbar and its effectiveness increases with increasing pressure. The amount of powder incorporated into the melt pool depends on the material and the scanning conditions. With identical scanning conditions, this amount of powder is significantly larger for titanium than for steel. For process pressures above 200 mbar, no significant change in the amount of spattering could be found. In this pressure range improved process stability could be possible due to a reduced laser/plasma interaction and an increased laser penetration depth.

Keywords Additive manufacturing · Powder bed fusion · Vacuum · Powder denudation · Single track · Spatter

1 State of the art

Laser powder bed fusion (LPBF) is a production method in the field of metal additive manufacturing, which allows to fabricate parts in unique shapes with outstanding mechanical properties [1, 2]. It has the potential to be a disruptive technology in industries, where end-user customization is highly desirable, where production volume is small, and where end products in highly complex, functionalized geometries are demanded [3]. However, to exploit the full potential of LPBF, the process and its influence on the produced structures need to be well understood. One of these influencing factors is the process pressure. Lowering the process pressure is widely accepted to be beneficial for laser welding [4], a process closely

related to LPBF, but has rarely been investigated for LPBF except for a few studies [5–14].

In one of these studies, Matthews et al. [8] found for Ti64 that the key mechanism for the consolidation of powder particles to a melt track is governed by the process pressure. At atmospheric pressure, metal vapor, caused by superficial overheating in the laser/metal interaction zone, expands jet-like towards the laser beam. As a consequence, a gas flow towards the melt pool is induced. It is strong enough to entrain powder particles within a distance of several hundred μm adjacent to the melt pool [8, 12, 14]. A certain proportion of the particles is absorbed in the melt pool, while the other part becomes hot or cold powder spatter [9, 14, 15]. When the pressure is lowered and the gas flow regime is altered from continuum flow towards a molecular flow, two changes occur simultaneously. First, the expanding metal vapor is less focused, and second, no gas flow can be induced in the surrounding atmosphere, which is capable of entraining particles [8, 12, 14]. The metal vapor, which is expanding in all directions, transports adjacent powder particles away from the melt pool, so that they cannot contribute to the formation of the melt pool. Consequently, studies

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investigating LPBF with process pressure in the molecular flow regime [5–7, 9–11, 14] found increased powder spattering [8, 14, 16], but no clear evidence for any LPBF process improvements. A process pressure in the continuum flow regime and below atmospheric pressure has been investigated much less. Bidare et al. [12] and Guo et al. [14] found that in the continuum flow regime powder spattering is reduced in comparison to the molecular flow regime. Matthews et al. [8] and Bidare et al. [12] could show that track formation due to powder entraining is enabled. However, there is no study investigating LPBF tracks and the surrounding affected powder layer for process pressures above 20 mbar, although Bidare et al. [12] already concluded that the pressure regime between 50 mbar and 1 bar could provide an interesting window, but that further investigation is required, as no evaluations of the spattering and LPBF tracks are available for this process pressure range. In addition, only minor technical adjustments would be required for the system implementation in this pressure regime.

In this work, LPBF single tracks are generated in the process pressure range from 1 mbar to atmospheric pressure. Although, as mentioned above, the interesting range is from 50 mbar to 1 bar, the investigated range is expanded to 1 mbar in order to determine the transition from the molecular to the continuum flow regime. The affected powder layer adjacent to the single tracks is 3D scanned, visualized, and evaluated. Surface profiles and cross sections for the materials CP titanium and Maraging steel are calculated. Powder spattering between 200 mbar and atmospheric pressure is quantified for the first time. The findings are discussed in the light of the previously presented literature to assess whether a process with reduced process pressure can provide benefits over a process at atmospheric pressure.

2 Experimental details

In the present work commercially pure (CP) titanium grade 2 (TLS Technik Spezialpulver™, Germany) with the sieve fraction 15–53 μm and Maraging steel 1.2709 (LPW M300, LPW™, UK) with the sieve fraction 15–45 μm were used. Table 1 summarizes the particle sizes measured with a laser diffraction particle size analyzer (Malvern Mastersizer 3000, Malvern™, UK), and the tap/bulk density according to ASTM B527 for both powders. The chemical analyses are TLS specification values for titanium and actual values for steel measured by LPW. The scanning electron microscopy (SEM) images in Fig. 1a and b show the spherically shaped titanium and steel powder particles with small satellites.

The LPBF experiments were performed on an AconityLAB (Aconity™, Germany) machine equipped with a 1064 nm, 400 W fiber laser (YLR-400-AC, IPG™, USA), a Raylase SUPERSKAN-II-E-20 2D laser scanner, and a F-Theta that sets a spot size of 50 μm on the building area. A Hena 61 (Pfeiffer Vacuum™, Germany) vacuum pump was used to evacuate the building chamber. Process pressures between 1 mbar and 950 mbar (atmospheric pressure) were controlled using an EVR 116 control gauge (Pfeiffer Vacuum™, Germany) to regulate the pumping rate (downstream pressure control) while constantly purging the system with argon. For the pressure measurement, the pressure gauge PCR 280 (Pfeiffer Vacuum™, Germany) was used.

With a coater blade, a powder layer of $60 \pm 5 \mu\text{m}$ was applied to a $\varnothing$ 70 mm substrate plate made of the respective material. Tracks with a length of 10 mm, referred to below as single tracks, were produced with different scanning parameters and different process pressures (see Table 2). The linear energy density, defined as the ratio of laser power to scanning speed, was kept constant in all experiments to ensure the comparability of the results in terms of energy input. According to [13], an adaption of the process parameter in low pressure conditions is necessary. Therefore, preliminary test was carried out and 0.16 J/mm was found to be a suitable linear energy density for both titanium and Maraging steel processed with a 50 μm laser spot. The single tracks were made at a distance of 5 mm from each other to avoid mutual influence. An Infinite Focus-Portable G1 (Bruker Alicona™, USA) focus variation microscope was used to gather 3D scans of each track in two different states with a resolution of 2 μm . The first scan was made within the process chamber, with the loose powder layer still on the substrate plate. The second scan was made after removing the powder, thereby exposing solely the consolidated single tracks. For the further evaluations, the 3D data 1.5 mm after the start and 1.5 mm before the end of the respective track (longitudinal direction) and ± 1 mm from the track center (transverse direction) were used. A description of the process of data acquisition and evaluation can be seen in Fig. 2.

The 3D data were displayed as height maps (see Figs. 3 and 4) and were used to calculate transverse profiles. This was done by calculating the mean z-height along y-direction for every data point in x. The resulting curves in Fig. 5 represent the mean surface profile of the powder bed and the single track. The mean cross-sectional area (see Fig. 6a) was evaluated by integrating over transverse single track profiles (without powder layer) at a sampling interval of 300 μm (23 measurements for each parameter set) and by calculating mean values and standard

Table 1 Powder properties

Name	Description	Supplier	Particle size	Powder density	Chemical analysis
Titanium	CP titanium grade 2	TLS	D10: 21.9 μm D50: 35.2 μm D90: 54.7 μm	Bulk: $2.47 \pm 0.06 \text{ g/cm}^3$ Tap: $2.82 \pm 0.04 \text{ g/cm}^3$	C: < 0.08 wt.% Fe: < 0.30 wt.% O: < 0.25 wt.% N: < 0.03 wt.% H: < 0.0125 wt.% Ti: Bal.
Steel	Maraging steel 1.2709	LPW	D10: 16.6 μm D50: 28.6 μm D90: 48.7 μm	Bulk: $4.35 \pm 0.10 \text{ g/cm}^3$ Tap: $4.83 \pm 0.10 \text{ g/cm}^3$	Ni: 17.7 wt.% Co: 9.2 wt.% Mo: 4.7 wt.% Ti: 1.1 wt.% Cr: 0.13 wt.% Si: 0.02 wt.% Mn: 0.02 wt.% O: 0.02 wt.% C, P, S, N: < 0.01 wt.% Fe: Bal.

deviations. The mean cross-sectional area of a single track is a measure for how much powder was consolidated under certain conditions. It does not consider molten/solidified substrate material. The change of spattering relative to atmospheric pressure (Fig. 6b) was calculated for process pressures ≥ 200 mbar and for the laser parameters 113 W/700 mm/s, which are closest to typical atmospheric pressure parameters. Calculation was done according to

$$rel.spatter(p) = \left(\frac{P(p) - COR}{P_{atmospheric}} - 1 \right) \cdot 100 \quad (1)$$

$$COR = \frac{S(p) - S_{atmospheric}}{PD} \quad (2)$$

where p is the process pressure, PD the powder layer density, S the cross-sectional area of the single track, and P the disturbed powder bed area (see Fig. 2).

Formula (1) calculates the relative amount of spatters at a given process pressure compared with ambient pressure by

comparing the areas S and P . The area P is a measure for the powder that is missing compared with the initial, undisturbed powder layer. The missing powder was either transported more than ± 1 mm from the center of the track or contributed to the single track. Therefore, comparing the difference of the areas P at a given process pressure to atmospheric pressure shows the relative change in spattering for a constant single track cross-sectional area. Since the single track cross-sectional areas, and therefore the amount of powder that contributed to the single track, are slightly different for different process pressure (see Fig. 6a), the correction term COR is introduced in formula (1). A single track is assumed to be fully dense; therefore, the difference in the single track cross-sectional area needs to be divided by PD , the density of the powder layer. For PD the relative bulk densities of the Ti and steel powder were used. According to the results in [17] the bulk density marks a lower limit for the powder layer density of typical LPBF powders at a layer thickness of 60 μm . Therefore, the calculations presented here represent the upper

Fig. 1 SEM images of **a** CP titanium grade 2 and **b** Maraging steel 1.2709 powder

Table 2 Scanning parameters and process pressures for single tracks. For every set of parameters, one single track was produced

Material	Name	Laser power (W)	Scanning speed (mm/s)	Linear energy density (J/mm)	Process pressure (mbar)
CP titanium Grade 2	T1	113	700	0.16	1, 3, 5, 10, 50, 100, 200, 500, 750, 950
	T2	225	1400		
Maraging steel 1.2709	S1	113	700	0.16	
	S2	225	1400		

limit for the amount of spattering. The relative bulk densities of 0.55 ± 0.1 for Ti and 0.54 ± 0.01 for steel were calculated using the theoretical densities of 4.5 g/cm^3 for Ti and 8.0 g/cm^3 for the Maraging steel 1.2709 and the bulk densities in Table 2. The error of the relative amount of spatters was calculated by considering the effects of error propagation.

3 Results and discussion

The height maps of titanium (T1 and T2) and steel (S1 and S2) single tracks produced with various laser parameters and process pressures are presented in Fig. 3. The surface profiles in transverse direction of the same single tracks are found in Fig. 5a–d as red lines. Both figures reveal that for process pressures ≤ 10 mbar, only a small amount (T1, T2, and S2) or no (S1) powder contributes to the formation of the single track. Almost only substrate plate material is remelted. The cross-sectional area of the single tracks in Fig. 6a confirms this finding as well. Furthermore, track S2 was accompanied by an adjacent depression on the substrate. This phenomenon is well known in laser welding and is referred to as undercutting [18]. It occurs at high welding speeds when wetting of the sides of the weld seam is prevented because the backflow of liquid metal is too high due to Marangoni convection [18–20]. Besides the lack of significant incorporation of powder into the single track for process pressures ≤ 10 mbar, the height maps in Fig. 4 and the corresponding surface profiles, gray lines in Fig. 5a–d, reveal that

exposing a loose powder layer to high power laser radiation leads to a significant powder denudation adjacent to the single track. Between 1 mbar and 10 mbar, the width of the denuded zone decreases with increasing pressure, while the shape of the powder layer surface remains similar: A zone entirely free of loose powder adjacent to the single track accompanied by a pile up. Since the area of the denuded zone in Fig. 5 is larger than that of the pile up, it can be concluded that a significant amount of powder was ejected further outward. The data in Fig. 5 show that the described behavior is found for both titanium and Maraging steel, but the laser parameter alters the strength of its appearance. Higher laser speed and power lead to a wider area where the powder layer was visibly influenced.

The reason for the occurrence of the denudation zone and the missing contribution of the powder to the formation of the single track lies in the high mean free path of the argon atoms of the process atmosphere for pressures ≤ 10 mbar. Free molecular flow is predominant. The metal vapor expands freely, entrains powder particles, and moves them away from the melt pool [8, 12]. This powder repelling mechanism prevents powder from being incorporated into the melt pool.

With increasing pressure, the mean free path of the atoms in the process atmosphere is reduced and the gas flow regime is changed from molecular flow towards a continuum flow [8]. The amount of consolidated powder rises, because the metal vapor flux does not expand freely as at lower pressure but interacts with the process atmosphere [8, 14]. The vapor flux expands jet-like in direction of the laser beam and induces

Fig. 2 Procedure for data acquisition and evaluation

Fig. 3 Height maps after removing the powder of single tracks made of CP titanium grade 2 and Maraging steel 1.2709 produced with various laser parameters and process pressures. T1 (titanium)—113 W,

700 mm/s; T2 (titanium)—225 W, 1400 mm/s; S1 (steel)—113 W, 700 mm/s; S2 (steel)—225 W, 1400 mm/s

a gas flow towards the melt pool, which has an about 10 times lower velocity than the metal vapor jet itself [21]. It is capable of efficiently entraining powder particles [8, 12, 14] and moving them towards the melt pool. A zone entirely free of powder particles adjacent to the single track and the corresponding pile up are no longer found. Rather, an area emerges in which shares of the powder layer are missing at a certain distance from the single track. This explains that at process pressures > 10 mbar, the height (Fig. 3) and the cross-sectional area (Fig. 6a) as well as the red line in Fig. 5) of the single track increase. This statement applies to both titanium and Maraging steel, processed with both 113 W/700 mm/s and 225 W/1400 mm/s. Figures 4 and 5 also reveal that the amount of powder incorporated into the melt pool depends on the

material used. With identical scanning conditions, this amount is significantly larger for titanium than for steel. Figure 5 reveals that with Maraging steel the single track is entirely covered with powder. This means that under the process parameters used, the steel powder is transported in the direction of the single track by the mechanism discussed above but is not completely melted. It can be concluded that the temperature of the single track was already below the solidus temperature before this transportation process was completed.

For all experiments, the cross-sectional area of the single tracks at process pressures between 200 mbar and atmospheric pressure varies by a maximum of 31% (28% for T1, 17% for T2, 26% for S1, and 31% for S2). For titanium and the Maraging steel, as shown for T1 and S1 in Fig. 6b, the

Fig. 4 Height maps of single tracks with surrounding powder layer made of CP titanium grade 2 and Maraging steel 1.2709 produced with various laser parameters and process pressures. T1 (titanium)—

113 W, 700 mm/s; T2 (titanium)—225 W, 1400 mm/s; S1 (steel)—113 W, 700 mm/s; S2 (steel)—225 W, 1400 mm/s

Fig. 5 Mean transverse profiles of the substrate plate, the single track surface (red line), and the surface of the powder layer (gray line) produced with various laser parameters and process pressures. The gray area represents the cross-sectional area of the powder layer. **a** T1 (titanium)—113 W, 700 mm/s; **b** T2 (titanium)—225 W, 1400 mm/s; **c** S1 (steel)—113 W, 700 mm/s; **d** S2 (steel)—225 W, 1400 mm/s

spattering in the pressure range from 200 mbar to atmospheric pressure does not change significantly within the uncertainty of the method used. Spattering increases by 12% at 200 mbar for S1 and less than $\pm 5\%$ for all other parameter sets related to the value determined at atmospheric pressure. This lies within typical process variations.

In the LPBF process at reduced process pressure below ~ 50 mbar, previous studies have shown that the amount of disruption in the powder layer [12] and the amount of spatters [14] increase significantly compared with the process at atmospheric pressure. Here, for the first time, LPBF in process pressure $200 \text{ mbar} \leq p < 1 \text{ bar}$ has been identified in which the quantity of spatters is similar to the process at atmospheric pressure, while the individual tracks show only slight changes in the cross-sectional area. This opens the possibility for an improved process due to enhanced laser penetration depth at $200 \text{ mbar} \leq p < 1 \text{ bar}$, but needs further investigation.

4 Conclusion and outlook

Increasing the process stability is one of the greatest challenges in order to fully exploit the potential of LPBF. One suggested approach is to perform the LPBF process under vacuum. In laser welding, a process closely related to LPBF, spattering was found to be significantly reduced when conducted in vacuum [4]. For the question of whether the benefits

of vacuum laser welding can be transferred to vacuum LPBF, the results of this work together with a thorough evaluation of the available literature allow the following conclusions to be drawn:

- The incorporation of powder particles into the melt pool via a gas flow induced by directional evaporation begins to be effective in the continuum flow regime at process pressures > 10 mbar. This incorporation changes significantly < 200 mbar and less at pressures ≥ 200 mbar. For both CP titanium grade 2 and the Maraging steel 1.2709 under the scanning parameters employed the cross-sectional area of the single tracks above this pressure change less than 31%.
- The amount of powder incorporated into the melt pool is different for CP titanium grade 2 and Maraging steel 1.2709. With identical scanning conditions, this amount of powder is significantly larger for titanium than for steel.
- The amount of spattering at process pressures above 200 mbar does not change significantly for CP titanium grade 2 and for the Maraging steel 1.2709 for 113 W/700 mm/s.
- Since the interaction between the laser beam and the plasma plume decreases with decreasing pressure, a potentially advantageous process window opens at pressures from ≥ 200 mbar to atmospheric pressure. For laser welding, it was found that with less interaction the penetration depth of the laser beam doubles when the pressure is reduced from atmospheric pressure to 30 mbar [4]. A significant increase in penetration depth was also found for LPBF when lowering the pressure to 50 mbar [12]. An increase in the laser penetration depth can also be expected for LPBF, when the pressure is reduced to 200 mbar. This needs to be investigated in further studies.

Fig. 6 **a** Mean cross-sectional area of single tracks produced with various laser parameters and process pressures evaluated by integrating over transverse single track profiles (without powder layer) at a sampling interval of 300 μm . **b** Relative change of spattering compared with

atmospheric pressure for process pressures ≥ 200 mbar. T1 (titanium)—113 W, 700 mm/s; T2 (titanium)—225 W, 1400 mm/s; S1 (steel)—113 W, 700 mm/s; S2 (steel)—225 W, 1400 mm/s

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