



2 State of the Art

To systematically develop a more productive PBF-LB/M process, this chapter will provide a comprehensive review of the fundamental principles of the process, with a specific focus on the current state of research related to the processing of AlSi10Mg alloy using PBF-LB/M. Particular attention will be given to understanding melt pool formation and its correlation with key process parameters, as this is essential for optimizing the efficiency and quality of the manufacturing process.

2.1 Additive Manufacturing

Additive Manufacturing (AM) is defined by the ISO/ASTM 52900 standard as a process of joining materials to produce parts from 3D model data. [8] This process is characterized by its incremental, layer-by-layer fabrication approach. [5] In contrast to conventional manufacturing techniques, which typically involve the removal of material to form the final part, AM methods build components by successively adding materials, resulting in near-net-shape or fully net-shaped parts. [9] This layer-based approach offers significant design freedom, enabling engineers to focus on the functionality of the parts and allowing for greater creativity in design. It also facilitates rapid prototyping, providing a fast and efficient way to test and iterate designs.

Despite initial limitations, AM techniques – such as PBF-LB/M – have matured significantly over past decades, opening pathways toward broader industrial adoption and mass production.

The growth of the AM market reflects this progress. In 2023, the global AM market for products and services grew by 11.1%, reaching \$20.04 billion, following a notable 18.3% increase to \$18.03 billion in 2022. Approximately, one-third of this market is attributed to AM for metals, with the PBF-LB/M process accounting for nearly 40% of that segment. [8]

2.2 Process Fundamentals

The PBF-LB/M process is a well-established additive manufacturing techniques for metallic materials, already widely adopted in various industries such as aerospace, automotive, and medical. [8] The PBF-LB/M process typically involves three steps: data preparation, printing, and post-processing.

During the data preparation phase, often referred to as slicing, the CAD-model of the parts is converted into an STL-format using triangulation. Subsequently, regardless of the part's orientation within the build chamber, the model is sliced into individual layers that correspond to the selected layer thickness. Each layer has a normal vector perpendicular to the substrate plate, as indicated in Figure 2.1.

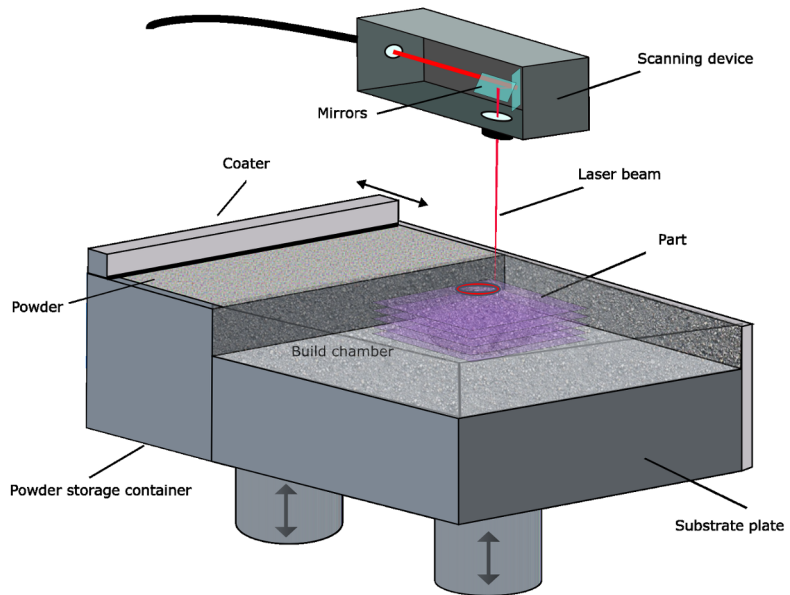


Figure 2.1: Schematic illustration of the PBF-LB/M-process

Depending on the scan strategy to be used, scan vectors are generated according to the part's cross-sectional geometry for each layer. This information is then communicated to the machine, setting the stage for the subsequent printing process.

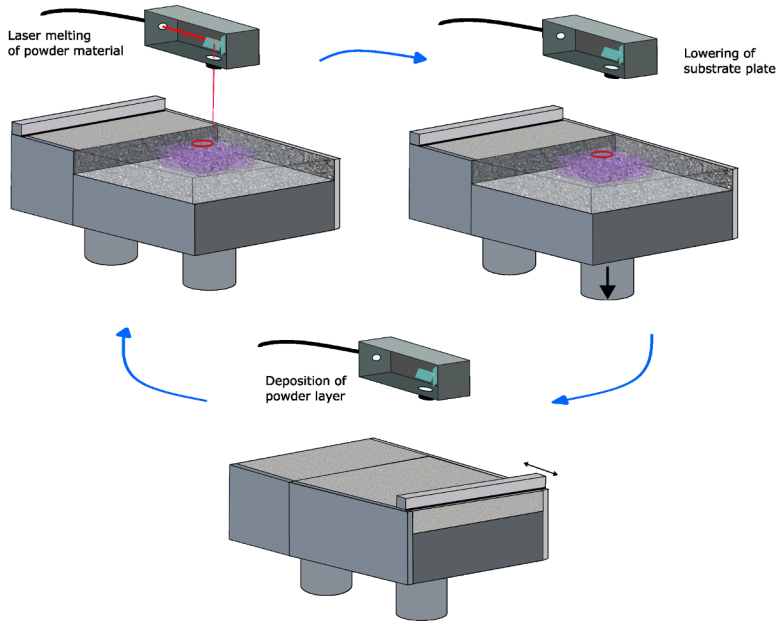


Figure 2.2: Schematic illustration of the repeating process steps of PBF-LB/M

The manufacturing process, as depicted in Figure 2.2, consists of three repetitive steps. First, a thin layer of the powder material, with a typical layer thickness d_s of 20 μm - 100 μm [10] is evenly distributed across the substrate plate using either a roller or blade. In the second step, the cross-sectional area of the part is selectively melted by the focused laser beam, following the defined scan strategy. Finally, in the third step, the substrate plate is lowered by one layer thickness, and the process is repeated. These steps are repeated continuously until the entire part is fully manufactured. The consolidation during the process is achieved through the complete melting of the powder and its fusion with the previously solidified layer. When appropriate process parameters are applied, this results in parts with near-100% density. The mechanical properties of these as-built components are comparable to those produced through conventional manufacturing methods.

2.2.1 Laser Induced Melt Pool Formation

Particularly in PBF-LB/M, the formation of a melt pool via the application of a moving high-intensity laser beam to a material's surface is a fundamental process in thermal energy conversion. In this process, the energy of the laser is absorbed by the material and converted into heat, raising the material to and beyond its melting point. As a result, the material melts and coalesces into a melt pool on the surface. Once the laser beam is redirected, the melt pool cools down and solidifies. This phenomenon is also used in other industrial manufacturing processes, including welding, drilling, and cutting. [11] The quality of melt pool formation plays a critical role in determining the overall quality of the resulting part. Consequently, a comprehensive understanding of this phenomenon is essential for optimizing process parameters and enhancing the performance of the PBF-LB/M process.

However, the absorption of the laser energy on the material's surface is generally not homogeneous. This inhomogeneous absorption leads to temperature gradients, which in turn result in heat flows. [12] The temperature gradient at the surface of the melt pool induces surface tension gradients, driving a surface flow.[13] Due to the viscosity of the liquid metal, the entire melt pool is set into motion. At even higher temperatures, evaporation may occur, and the accompanying recoil pressure further affects melt pool dynamics, leading to the denudation of powder surrounding the melt track, a phenomenon particularly relevant in the PBF-LB/M process. [14], [15] The interplay between these physical phenomena is summarized in Figure 2.3:

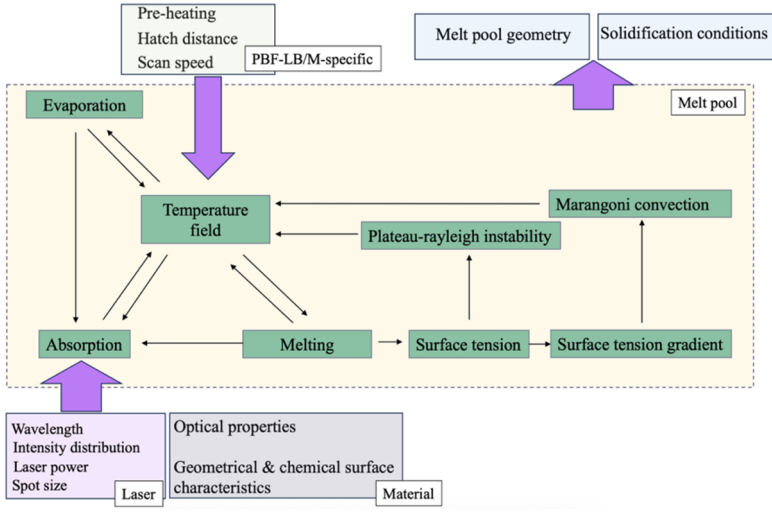


Figure 2.3: Physical phenomena and their interplay in shaping the melt pool. Adapted from [16].

These melt pool dynamics arise from the interaction of the aforementioned factors, and they play a crucial role in influencing both the dimensions of the melt pool and the subsequent solidification conditions. [15]–[17]

The absorptivity of a material is influenced by several factors, including the wavelength, polarization, and angle of incidence of the laser, as well as the material's properties, such as the optical constants, geometrical state (e.g. surface roughness), and chemical state of the surface (e.g. oxide). These material properties are all temperature-dependent. [11]

Metallic materials, in particular, tend to have a high reflection coefficient R [%], and for metals of sufficient thickness, the transmission coefficient T [%] is negligible [11]. This leads to the following relationship:

$$A = 1 - R \quad (2.1)$$

where A [%] represents the absorptivity of the material.

For describing the absorption of electromagnetic radiation and the associated optical constants of metals, the Drude model, in its modified form, is still widely used today due to its clarity and simplicity. This model, particularly in the infrared region, has been shown to provide reasonable

approximation for absorptivity when adapted to account for quantum mechanical effects. [11], [17], [18]

Figure 2.4 illustrates the variation in absorptivity of different solid metals as a function of the incident laser wavelength, based on calculations using the Drude model and interband transitions by Bergström et. al. [19]

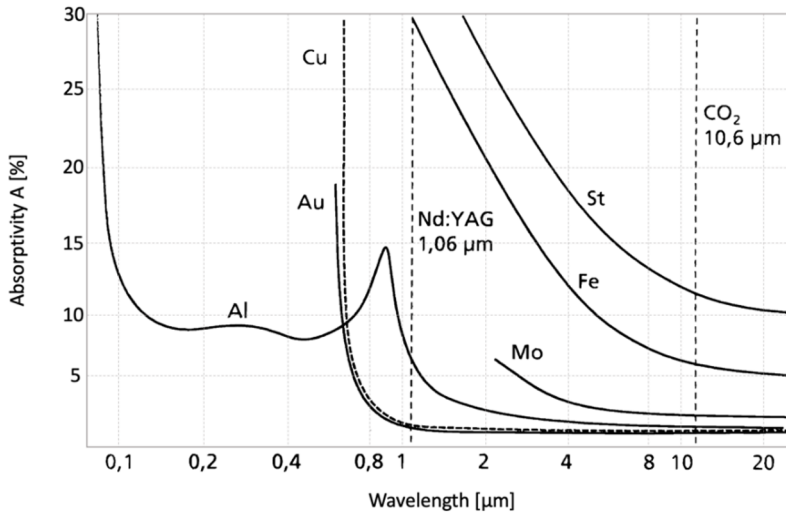


Figure 2.4: Absorption as a function of wavelength between UV and IR for different metals based on Drude-model. [19]

Figure 2.4 demonstrates that the absorptivity of certain materials is highly dependent on the wavelength of the incident laser. For example, aluminum exhibits significantly higher absorption compared to copper or gold at a wavelength of 1.06 μm , which is commonly utilized in PBF-LB/M processes.

These values are for solid bulk metals, however, the duration of the laser-material interaction of the laser radiation with the specific volume of powder is considerably larger than the time needed to melt this volume. Therefore, the large part of the laser radiation absorption happens in the liquid state of the material. [20] This is because the optical penetration depth δ_{op} for most metals is in the range of 10s of nanometers, as indicated in Figure 2.5. [16], [21]

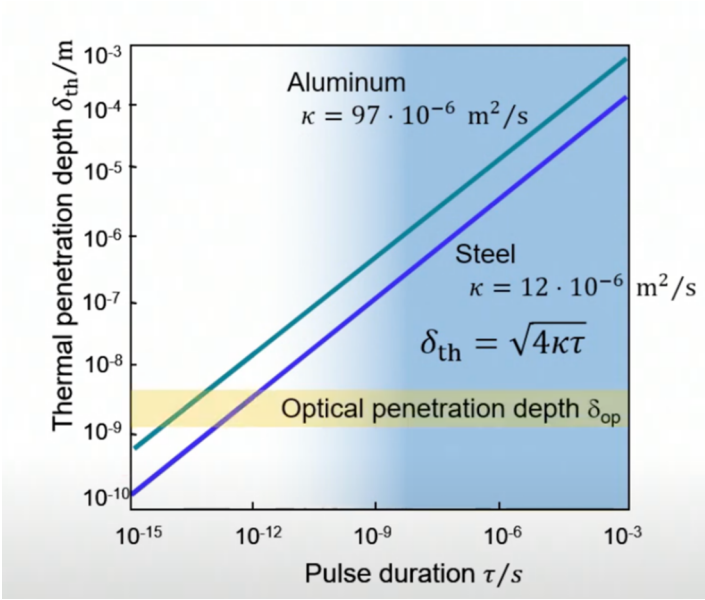


Figure 2.5: Optical penetration depth δ_{op} of aluminum and steel. [21]

The absorptivity of aluminum experiences a jump when transitioning from the solid state to the liquid state, as shown in Figure 2.6. According to Funck and Holtz [22], [23], crossing the melting point the absorptivity is more than doubled, with respect to ambient temperature absorptivity.

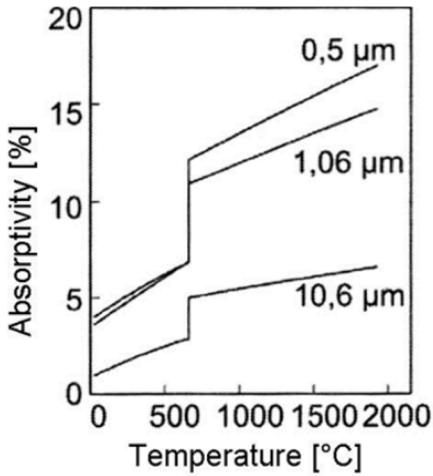


Figure 2.6: Absorptivity of aluminum in dependency of temperature and wavelength. [22]

In general, an increase of the absorptivity of metals with rising temperatures is observed in experiments and documented in the literature. [11], [16], [22], [24]–[26]

2.2.2 Melt Pool Dynamics

The Marangoni convection is a well-documented effect that describes the convection current driven by surface tension gradient, which, in turn, is caused by the temperature gradient at the melt surface. [11], [13] The direction of the convection flow induced by this phenomenon depends on the shear stress τ_s , which is a function of the surface tension gradient with respect to temperature $\frac{d\sigma}{dT}$, a material-dependent property. For most pure metals, surface tension gradient $\frac{d\sigma}{dT}$ is typically negative, resulting in an outward flow of the center of the melt pool – where the temperature is the highest – toward the edges in the radial direction. This outward flow tends to create a shallow and wide melt pool. [13], [27]–[29] The reason for this is as the liquid material is transported outwards from the center position, the temperatures in these areas increase. Due to this mass transport, less heat is transferred in the downward direction, leading to a decrease in melt pool depth. At the edges of the melt pool, the shear stress induces a flow along the solidus-liquidus interface, while at the bottom center of the melt pool, the flows from both sides converge and move upward, forming two characteristic vortices and affect the heat transfer, as schematically illustrated in Figure 2.7. [11], [13]

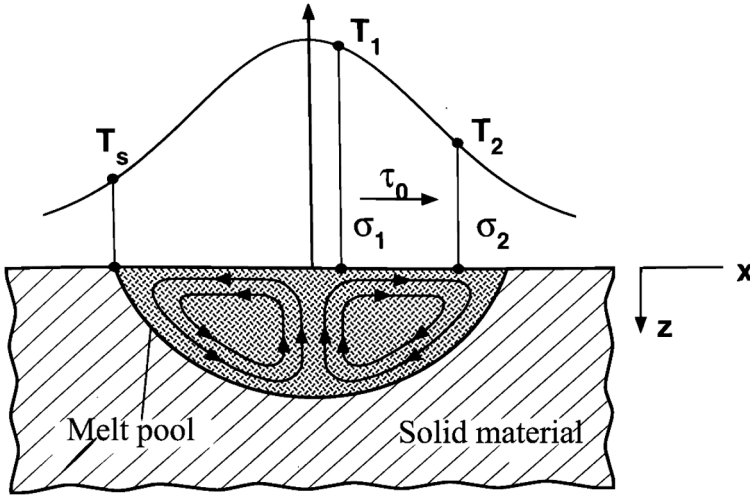


Figure 2.7: Schematic illustration of the melt pool flow induced by the Marangoni effect in case of a negative surface tension gradient $\frac{d\sigma}{dT}$. Adapted and modified from [13].

When the surface tension gradient $\frac{d\sigma}{dT}$ is greater than 0, the Marangoni-driven flow goes in the opposite direction as that of one shown in Figure 2.7. This behavior has the opposite effect on the melt pool compared to the aforementioned one: the heat transport increases towards the inside of the workpiece leading to a larger melt pool depth. Consequently, the temperatures of the outer areas of the melt pool decrease leading to a decrease in melt pool width.

Relevant results from Gan et al. [30] in the context of PBF-LB/M show that a substantial portion of the heat transport within the melt pool is attributed to the convective heat transfer induced by the Marangoni flow. This convective flow not only enhances heat transfer but also promotes mixing within the melt through mass transfer, improving the fusion between the current layer and the underlying layer. However, while the increased flow velocity driven by Marangoni convection can be beneficial for heat transfer and material mixing, it may also reduce the stability of the melt pool. [31]–[33] Moreover, study has demonstrated that the influence of Marangoni convection decreases when the scan speed is within or above

the range of the flow velocity (approximately in the range of 500 mm/s as determined by [34]). [35]

In conclusion, the formation of the melt pool in laser-based processes is a highly complex physical phenomenon, influenced by a wider range of factors. Convection, particularly Marangoni convection, is one of the most significant factors affecting melt pool geometry. [36]–[38]

2.2.3 Melt Track Formation

To form a coherent and stable melt track in the PBF-LB/M process, a sufficient amount of energy must be delivered into the powder bed. Taking into account absorptivity and melting enthalpy, the energy required to form a continuous melt track is typically an order of magnitude larger than the energy needed to melt an equivalent volume of the material alone. [39] As the fundamental building blocks of the manufactured using PBF-LB/M, melt tracks must form effectively and achieve proper fusion with the underlying material.

If the energy input is insufficiently, the resulting melt tracks become irregular and may fragment into smaller segments. With even lower energy inputs, these tracks can degenerate into a series of separated, spherical structures, a phenomenon known as “balling”. [15], [28], [40]–[44]

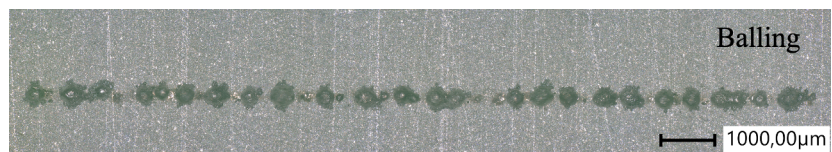


Figure 2.8: Top-view of a single track with balling occurrence

This effect, illustrated in Figure 2.8, occurs when the laser energy is sufficient to melt the powder but insufficient to adequately melt the underlying bulk material, thereby failing to establish a strong bond between the layers. In such cases, the melt pool is subject to Plateau-Rayleigh capillary instability, a tendency to form spherical droplets instead of continuous melt tracks to minimize surface energy. [15]

As a result, most process development approaches, particularly for unknown materials, utilize single-track experiments to determine suitable combinations of laser power and scan speed for delivering the minimum energy required for coherent and uniform melt tracks. These identified combinations are then further explored in subsequent development stages.

Another phenomenon, humping, well known in laser welding, is observed when welding at high speeds in keyhole mode. [13] Different explanations for the occurrence of this kind of track instability at elevated energy input are published. Its cause is considerably less understood than that of the “balling effect”.

Albright et al. [45] explained the occurrence based on the theory of Plateau-Rayleigh capillary instability. According to him, humping occurs when molten material is forced to flow around the keyhole edge resulting in a high velocity inside the central part of the melt behind the keyhole. The molten material reduces its widths to the center to reduce free surface energy. The melt band flows over the already solidified material with an elevation at the back of the melt pool, creating the periodic agglomerates of materials, as depicted in Figure 2.9. This explanation meets approval of numerous further research groups. [46]–[49] Foley et al. obtained a correlation between the humping occurrence and the Froude number Fr , which is defined as the ratio of the flow inertia to the external force field (gravity). He suggests an elongated melt pool in the scan direction to depress the likelihood of the humping occurrence, which is the opposite to what the theory of Plateau-Rayleigh would suggest. [50]

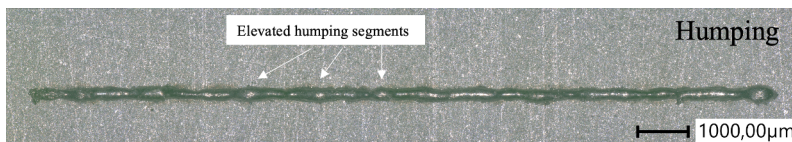


Figure 2.9: Top-view of a single-track with humping occurrence.

Lastly, evaporation affects the melt track formation during the PBF-LB/M process. The recoil pressure induced by evaporation deforms the melt track surface and contributes to spatter formation, thereby reducing process

stability. [15], [51]–[53] In general, evaporation is influenced by laser intensity and ambient pressure: higher laser intensities result in increased temperatures, while lower ambient pressures reduce the boiling point of the material. [54]

One notable effect of evaporation is the denudation of the surrounding powder bed, which occurs due to a pressure drop induced by the upward-moving vapor plume, as explained by Bernoulli's principle. [55]–[57] This effect reduces the available powder for the subsequent track, potentially leading to localized overheating in adjacent regions.

2.2.4 Process Parameters

In the PBF-LB/M process, the parameters are divided into four categories: (1) laser beam parameter: laser power, focus diameter, pulse duration, pulse frequency, etc., (2) process parameter: scan speed, hatch distance, exposure pattern, and exposure order, (3) powder parameter: particle shape, particle size distribution (PSD), layer thickness, packing density, material properties, and (4) thermal conditions: pre-heat temperature, powder bed temperature, temperature distribution. These above-mentioned factors are interdependent and have in some cases strong correlation to each other. For instance, the minimal laser power used depends both on the material, the ambient temperature as well as the scan speed, the absorption, and the packing density of the powder bed.

The following process parameters play a pivotal role in determining part quality due to their direct influence on energy input. This highlights the critical importance of carefully selecting and optimizing these parameters to ensure the desired part characteristics and overall process success:

The laser power P_L represents the real power at the focus spot with a diameter d_F . Depending on the optical setup, the laser power generated by the source is reduced. The spatial distribution of the power in the area of the focus spot is defined as the intensity profile I_F . The most common intensity profile utilized in the PBF-LB/M process is the gaussian profile generated by single mode lasers. [58] Other intensity profiles such as “top-

hat” or “donut” are also under investigation in the recent years. [15], [16], [59], [60] Despite determining the laser intensity, the focus spot size d_F also has significant impact on the accuracy of the PBF-LB/M process. A smaller spot size allows for building of finer details and smoother surface. The scan speed v_s is the velocity with which the laser spot moves across the building plane, with increasing scan speed the energy input decreases. The layer thickness d_s determines the resolution and precision of the final part. Thinner layers produce highly accurate details but may increase the process time. The hatch distance Δy refers to the distance between two adjacent scan vectors. It affects the amount of the overlap area of the neighboring scan tracks. An appropriate hatch distance ensures proper fusion between the adjacent tracks while minimizing defects such as lack of fusion. The widely used reference point to start a process development with is given by Meiners [61] as $\Delta y \approx 0.7 d_F$.

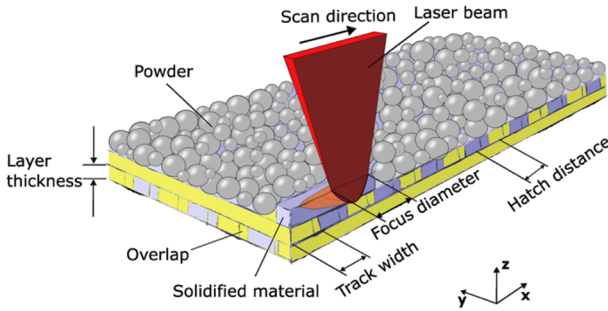


Figure 2.10: Schematic illustration of PBF-LB/M process parameters. Adapted from [4].

As indicated in Figure 2.10, choosing a hatch distance Δy smaller than the resulting track width leads to an overlap of two adjacent tracks. Depending on the material processed, overlaps can in some cases significantly reduce the lack of fusion defects and crack formation. However, the build-up rate decreases with decreasing hatch distance.

For PBF-LB/M process, the Andrew number [62], first introduced in 1993, is commonly extended by the layer thickness d_s to describe the volumetric energy density E_V that combines laser power P_L , scan speed v_s , hatch distance Δy and layer thickness d_s :

$$E_V = \frac{P_L}{d_s \cdot v_s \cdot \Delta y} \quad (2.2)$$

Both experimental and numerical works have been put into the optimization of the key process parameters to attain the intended part quality, mechanical characteristics, and dimensional precision. It is crucial to acknowledge the intricacy of the PBF-LB/M process, as factors beyond these parameters – such as inert gas atmosphere [63], preheating temperature [4], [64], scan strategies [65], [66], and particle size distribution (PSD), wettability and morphology of the powder [67], [68] – can exert additional influence on the ultimate results. The works by Wagner [69], Fährer [70], and Rehme [71] summarized over 150 influencing factors along the entire process chain.

In order to generate parts with a relative density of up to $\rho = 100\%$ by the means of the PBF-LB/M process, one of the important aspects to consider is to identify the appropriate process window. The complete melting of a layer of the powder material and the partial re-melting of the previous layer underneath are essential.

2.2.5 Process Defects

Process defects represent the primary constraints on part quality, which is a fundamental requirement for any PBF-LB/M process and its optimization. The occurrence of these defects is closely tied to the selection of process parameters and the prevailing process conditions.

The most common defects in PBF-LB/M manufactured parts are cracks, porosity, and deformation due to residual stresses. [4], [72], [73] There are generally two kinds of crack formation mechanisms when considering welding applications. [74] The cold cracking, also known as tension

cracking may appear in the fully solidified material when the thermal gradient-induced residual stresses exceed the material's strength. For hot cracking, that emerges from heated material, there are two cracking mechanisms, namely solidification and liquation cracking. While the solidification cracking is as well induced by the thermal gradient, the liquation cracking typically appears for alloy with a large solidification range in the heat affected zone around the melt pool, when low melting precipitations liquefy. [4], [75] As the eutectic Al-Si alloys AlSi10Mg have a small difference between solidus and liquidus temperatures, no liquation cracks are expected. As the thermal gradient is inversely proportional to the thermal conductivity, AlSi10Mg is less likely to exhibit to tension and solidification cracking. To further reduce the likelihood of these kinds of crack formations, the heating of the substrate plate is usually applied. Hence, crack formation is not often observed in the PBF-LB/M-produced AlSi10Mg parts.

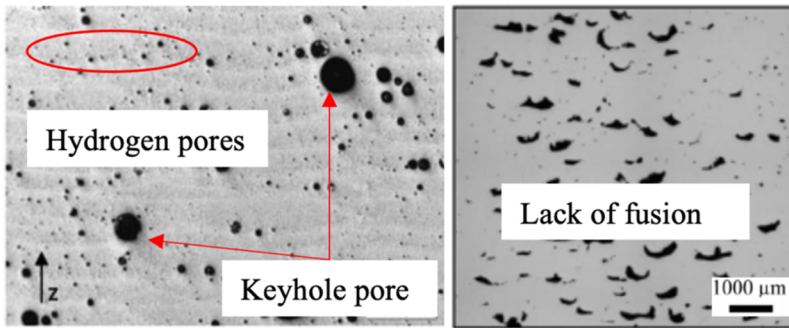


Figure 2.11: Examples of the porosity categories: left: keyhole and hydrogen porosities [76], right: lack of fusion porosity.[77]

Generally, three different categories of porosity are observed in the AlSi10Mg parts produced by PBF-LB/M process: keyhole porosity, metallurgical porosity (or gas porosity), and lack of fusion porosity. [72], [77]–[80] These defects are exemplarily shown in Figure 2.11. Keyhole pores are usually spherical and concentrate at the bottom of the melt pool. [58], [81], [82] They are formed by high volumetric energy density [82] [83] and the resulting keyhole fluctuation, as identified by research groups

using in-situ X-ray imaging. [84]–[86] While keyhole welding could greatly increase the applicable layer thickness in the PBF-LB/M process, its highly dynamic behavior makes it difficult to control, hence undesired for the process. The basic principles for the keyhole pore formation such as recoil pressure distribution on the keyhole surface, the relationship between energy and keyhole fluctuation and the influence of the convective flow of the melt pool are still not very well understood. [87] The simulative analysis by Wang et al. [87] suggests the unevenly distributed recoil pressure on the keyhole surface increases the possibility of keyhole collapse and form keyhole pores, hence, reducing the ambient pressure could suppress the formation of the keyhole pores because this could stabilize the recoil pressure.

Gas pores are generally spherically shaped and are caused by entrapped gases that cannot escape before solidification of the melt pool. These gases can come from the evaporation of low-melting constituents or the dissolution of oversaturated elements. The most common entrapped gas in the gas pores of AlSi10Mg parts is hydrogen. This is due to the high reactivity of aluminum to hydrogen. [73], [76], [77] The hydrogen mostly come from moisture or in the form of hydroxide on the surface of the powder particles. [88] Hydrogen pores are distributed almost homogeneously throughout the entire part. This phenomenon is attributed to the much higher hydrogen solubility in liquid aluminum compared to that in solid state, as schematically illustrated in Figure 2.12.

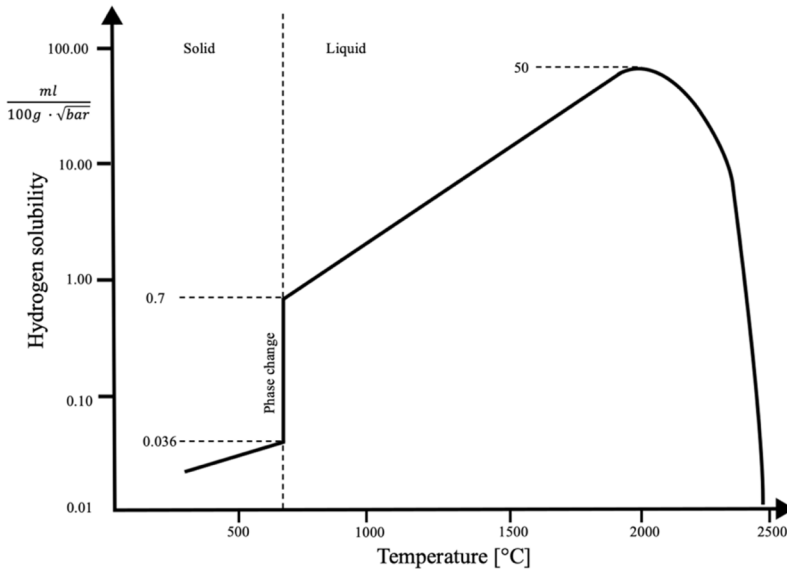


Figure 2.12: Hydrogen solubility in dependency of temperature and states of aluminum. Adapted from. [89]

When the aluminum is in its molten state, hydrogen dissolves into the melt. As the material cools and solidifies, the solubility of hydrogen decreases. However, due to the rapid cooling rate, the hydrogen content remains mostly unchanged, and there is minimal opportunity for diffusion-driven equilibration. As a result, hydrogen precipitates out of the solution, forming gas bubbles. These gas bubbles become trapped by the advancing solidification front, leading to the entrapment of hydrogen pores within the solid structure. The mechanisms underlying hydrogen porosity formation in aluminum during welding processes are well-documented in the literature. [89]–[93] Weingarten et al. [76] showed that drying the powder material prior to the process or in the process with low laser power prior to the exposure can significantly decrease the hydrogen content contained in the powder. Moreover, the authors suggest that a decrease of scan speed decreases the hydrogen pore density.

2.2.6 Productivity of PBF-LB/M Process

Productivity is a measure of economic performance that compares the amount of goods and services produced (output) with the number of inputs

used to produce those goods and services and time. The productivity of the PBF-LB/M process is considered as the volume generated per unit time. This can be calculated by dividing the amount of the parts built by the total time used. The total duration of the fabrication of a part includes the time of the data preparation, which stays mostly constant, independent of the numbers of the part, the melting process duration, and the post-processing duration, which increase proportional to the amount of the parts.

The melting process duration in the PBF-LB/M process can be defined as:

$$t_{total} = t_{exp} + t_{coat} + t_{delay} \quad (2.3)$$

$$= \frac{V}{ds \cdot v_s \cdot \Delta y} + \frac{z}{ds} \cdot t_{s_{coat}} + \frac{z}{ds} \cdot t_{s_{delay}} \quad (2.4)$$

With t_{total} is the total duration of the build job, which is comprised of three distinct temporal components: the exposure duration t_{exp} , the duration of coating t_{coat} , and delay of the scanner t_{delay} . These temporal intervals are strategically introduced both prior to and subsequent to each scan vector to rectify the inherent lag of the scanner mirrors, which results from the mechanical inertia of the mirrors. [94] The exposure duration t_{exp} is fundamentally defined as the time span during which the volume V of powder material is melted by the incident laser beam energy. The efficiency of the process can usually be mathematically characterized as the ratio between the component volume V and the product of the layer thickness ds , the scan speed v_s , and the hatch distance Δy , and it is defined as the volume energy E_V . The above-mentioned product is also referred to as the theoretical build-up rate v_{th} , symbolizing the rate of material melted per unit of time.

$$v_{th} = ds \cdot v_s \cdot \Delta y \quad (2.5)$$

This expression is solely dependent on the utilized process parameters and can therefore be transferred from one system to another. [59]

To effectively broaden the applicability of PBF-LB/M from limited prototype and small-scale production to full-scale industrial

manufacturing, a significant enhancement in the process's build-up rate and consistency is imperative. Advancements in these areas are anticipated to yield substantial economic efficiencies and ecological benefits. [95]

The theoretical build-up rate v_{th} , a critical metric of productivity particularly in relation to the laser exposure phase, is determined by the volume of material that can be melted and solidified within a specific timeframe. It is often quantified in cubic centimeters per hour [cm^3/h], and is highly contingent on the laser power P_L . Material-dependent physical constraints exist; for instance, insufficient energy input may result in 'lack of fusion' defects, while excessive energy can cause issues such as keyhole porosity, and material vaporization. Identifying an optimal compromise between the build rate and the stability of the process is crucial for reliable operations.

To augment the build rate within the PBF-LB/M domain, two primary strategies are advocated: implementing parallelization techniques to conduct simultaneous laser exposures and utilizing high laser power that are designed to maximize throughput and efficiency. [59]

Increasing the numbers of the operating lasers is a method that directly increases the build-up rate of a PBF-LB/M system. It involves the simultaneous utilization of multiple laser sources to melt the powder material. The increase in the build-up rate exhibits nearly linear in proportion to the number of laser sources employed. Nonetheless, challenges emerge concerning the metallurgical connections with the regions where multiple lasers operate on the same component. [59] Achieving synchronization of the exposures, which depends on the geometrical attributes of the parts, necessitates the development of a specialized algorithm. [96] It is important to note that the augmented investment required for the system constrains the maximum number of lasers that can be employed.

The second common approach to increase the theoretical build-up rate is to increase the laser power that are utilized for the process. This approach can

usually increase the build-up rate without increase the efficiency of the process; i.e. proportional build-up rate increases to the increase of the laser power. Schleifenbaum's work [97] showed that this approach leads to higher build-up rate for materials that have high thermal conductivity. For materials with lower thermal conductivity, the increase of the build-up rate is lower. For this conclusion, a single mode laser with a gaussian intensity distribution was used and its impact on the process was systematically investigated. Using high laser power and gaussian profile led to a large temperature rise in the region around the focal center. In dependence of the thermal conductivity of the materials, the maximum input energy per area is limited. Surpassing this limit, increasing evaporation, spatter formation, and keyhole welding effects are documented in [59], [60], [98]. In order to compensate the high laser power, higher scan speeds can be utilized up to a certain limit, at which humping or balling occur. [42] Powder denudation can be caused by the Bernoulli effect induced by vaporization of the melt pool. [14] Balling occurs at a critical length to diameter ratio of the melt pool; this effect is influenced by Marangoni flows and the Plateau-Rayleigh instability, as extensively discussed in Section 2.2.3. [44], [99] Due to these phenomena, a stable and reproducible process cannot be established. The application of zoom- / defocus optical elements could realize a smooth utilization of high laser power. [100] One notable promising technique for manipulating the laser intensity delivery is beam shaping, where the laser intensity distribution is adjusted to achieve a rather homogeneous temperature field. This approach will be discussed in Section 2.4.

2.3 Overview of Processing AlSi10Mg with PBF-LB/M

In the past decade, significant research endeavors have been directed toward elucidating the optimal process parameters that facilitate defect-free manufacturing across various materials. This pursuit often necessitates resource-intensive trial-and-error experiments. Metal additive manufacturing techniques, such as PBF-LB/M, entail a vast array of process parameters. These influence the notably high heat input and rapid cooling rates, typically on the order of $\dot{T} = 10^5$ K/s. [101] To simplify the

process development, key parameters such as laser power, scan speed, layer thickness, and hatch distance are identified. These parameters have a direct influence on the melting process. Furthermore, these key parameters are controllable process parameters limited by the capability and customizability of the machine.

Typically, these four process parameters are quantified using a measure called volumetric energy density E_V , a widely adopted metric for assessing energy input in PBF-LB/M. This approach is good enough for finding a process window (given by a minimum and a maximum E_V value), within which parts can be manufactured defect-free. Here are some examples for processing AlSi10Mg:

Two decades ago, Zhang [102] successfully generated three-dimensional specimens of aluminum alloys with a relative density of approximately 100%. In the dissertation, process windows for various aluminum alloys, including AlSi10Mg, AlMg3, AlSi25, and AlMgSi0.5, were developed. Utilizing a laser power of 300 W, a layer thickness of 50 μm , and a scan speed of 700 mm/s, dense parts of AlSi10Mg were produced, which exhibited comparable or superior mechanical properties to conventionally manufactured specimens.

Kempen et al. [103] developed a process window for three-dimensional specimens on a commercial PBF-LB/M system M1 from Concept Laser, utilizing a maximum laser power of 200 W and a focus diameter of 150 μm , achieving a relative density of 99.4%. This method is widely used in the industry, involving scanning of single tracks and the analysis of the track cross-sectional geometry in the plane perpendicular to the scan direction. The derived hatch distance and layer thickness are combined with the corresponding laser power and scan speed to generate three-dimensional parts. A maximum build-up rate of 4.4 mm³/s was achieved with a scan speed of 1400 mm/s at a laser power of 200 W.

Buchbinder's research [104] on high power PBF-LB/M process for AlSi10Mg demonstrated that the theoretical build-up rate could reach

around 20 mm³/s using a laser power of $P_L = 960$ W, achieving a relative density of $\rho \geq 99.5\%$. The disproportionate increase in scan speed, from 600 mm/s to 3500 mm/s, compared to the increase in laser power from 240 W to 960 W, can be explained by two factors:

1. Due to the mechanical limitations of the galvanic mirrors, the actual average scan speed over the powder bed was lower than intended. Without the skywriting function, the laser needs a longer acceleration distance at higher speeds.
2. Higher scan speeds shorten the cooling time of previously scanned tracks, raising the base temperature for the next track. This means less energy is needed to melt the neighboring track. This effect can be considered as local pre-heating.

Furthermore, Buchbinder investigated the influence of the pre-heating of the substrate plate on the defect formation of the process. A significant increase of gas pores could be observed with $T_{preheat} \geq 300^\circ\text{C}$, while the size of the gas pores increased when $T_{preheat}$ reached 400°C . Below $T_{preheat} = 200^\circ\text{C}$, no significant impact on porosity formation could be observed. [104]

However, exclusive reliance on the volumetric energy density E_V fails to account for the intricate interactions among these parameters, which makes the melting dynamics more complex. Consequently, to truly understand and optimize the melting process in PBF-LB/M, it is important to consider a broader perspective that encompasses how these parameters work together, not just individually. [52], [105]

2.4 Beam Shaping in PBF-LB/M

The alternative beam profiles to the Gaussian beam such as top-hat profiles and ring-shaped profiles were investigated by numbers of research groups. Most of them used diffractive optical elements [60], [106] or lenses [107]. The findings of the works [51], [108]–[114] on different materials such as aluminum-copper alloys, aluminum alloy 6061 (AA6061), CoCrMo, Ti6Al4V, and stainless steel processed by either ring-shaped or top-hat

intensity distribution are showing a wider process window and reduced spatter formation indicating more robustness of the process. This enables the usage of higher laser power that can translate into higher build-up rate without improving the process efficiency.

Wischeropp [15] numerically investigated the influence of a ring-shaped intensity distribution on melt pool characteristics. The simulation revealed that the ring-shaped intensity distribution reduces vaporization by over 40%, decreases thermos-capillary flow, and results in lower melt velocities compared to the Gaussian beam profile when using high laser power up to 900 W. Utilizing a diffractive optical element, Wischeropp experimentally validated the reduction of spatter formation during the process of both materials AlSi10Mg and AlSi16Sc. This effect is confirmed by other researcher's works. [51], [111], [112] Additionally, Wischeropp demonstrated the potential of the ring-shaped intensity distribution to increase the theoretical build-up rate v_{th} to up to 25 mm³/s, with following parameters: laser power $P_L = 900$ W, scan speed $v_s = 2500$ mm/s, hatch distance $\Delta y = 200$ μ m, and layer thickness $d_s = 50$ μ m.

Kohlwes [51] systematically investigated the influence of a ring-shaped intensity distribution, generated by the nLIGHT AFX-1000 laser, on spatter formation during Ti6Al4V processing. The study demonstrated that both the ring-shaped profile and a superposition of ring-shaped and Gaussian profiles significantly reduced spatter formation compared to a Gaussian profile alone. In a case study evaluating the economic impact of the increased build-up rate ($v_{th} = 72.4$ cm³/h), cost savings per print job of 16% - 31% were achieved.

Grünwald et al. [115] investigated the influence of a ring-shaped laser intensity distribution on melt pool formation—specifically the cross-sectional molten area and molten volume—using an in-house developed test rig with stainless steel AISI 316L sheets in a no-powder configuration. The results indicate that, at high laser power and scan speed, the process becomes stabilized, enabling a significantly wider process window

compared to that of a Gaussian beam, thereby suggesting increased robustness and stability.

Further research works, either numerically or experimentally, agree on the potential of alternative intensity distribution to Gaussian beam profile can directly influence the melt pool formation [107], [109], [110], [116], [117], hence, influence the process stability [116], the theoretical build-up rate [110], [116], [118] as well as mechanical properties [117] [119], microstructure [107], [109], [120], [121], [122] and surface roughness of the as-built specimens on a variety of materials. [118] However, systematic investigations on the process optimization in terms of maximizing the build-up rate and process efficiency in an industrial environment have not yet been published.