Chapter 5
Powder Bed Fusion

Abstract Powder Bed Fusion (PBF) was one of the earliest and remains one of the most versatile AM processes, being well-suited for polymers and metals and, to a lesser extent, ceramics and composites. There are an increasing number of machine variants for fusing powders using different energy sources. The most active area of development is for metal PBF processes using lasers. Laser-Based Powder Bed Fusion (LB-PBF) processes are of great interest across many industries as a means of direct manufacturing. This chapter will cover various approaches to PBF, issues surrounding the handling of powders, and the growing types of applications for these technologies.

5.1 Introduction

PBF processes were among the first commercialized AM processes. Developed at the University of Texas at Austin, USA, Selective Laser Sintering (SLS) was the first commercialized PBF process. Its basic method of operation is schematically shown in Fig. 5.1, and all other PBF processes modify this basic approach in one or more ways to enhance machine productivity, to enable different materials to be processed, and/or to avoid specific patented features.

All PBF processes share a basic set of characteristics [1, 2]. These include one or more thermal sources for inducing fusion between powder particles, a method for controlling powder fusion to a prescribed region of each layer, and mechanisms for adding and smoothing powder layers. The most common thermal sources for PBF are lasers. PBF processes which utilize lasers are known as laser sintering (LS) machines. Since polymer laser sintering (pLS) machines and metal laser sintering (mLS) machines are significantly different from each other, we will address each separately. In addition, electron beam and other thermal sources require significantly different machine architectures than laser sintering machines. Non-laser thermal sources will be addressed separately from laser sources at the end of the chapter.

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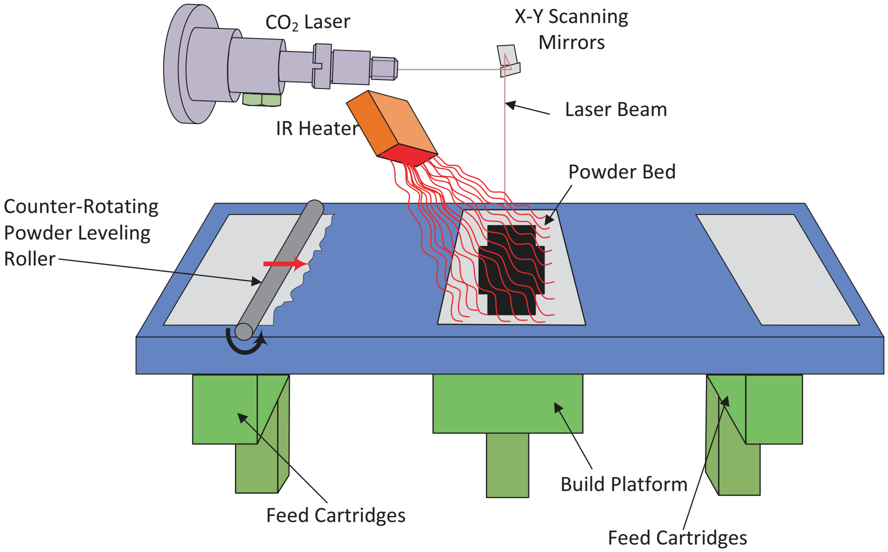


Fig. 5.1 Schematic of the Selective Laser Sintering process

LS processes were originally developed to produce plastic prototypes using a point-wise laser scanning technique. This approach was subsequently extended to metal and ceramic powders; additional thermal sources are now utilized; and variants for layer-wise fusion of powdered materials have been commercially introduced. As a result, PBF processes are widely used worldwide, have a broad range of materials (including polymers, metals, ceramics, and composites) which can be utilized, and are increasingly being used for direct manufacturing of end-use products, as the material properties are comparable to many engineering-grade polymers, metals, and ceramics made using conventional means.

In order to provide a baseline description of PBF processes, polymer laser sintering (pLS) will be described as the paradigm approach to which the other PBF processes will be compared. As shown in Fig. 5.1, pLS fuses thin layers of powder (typically 0.075–0.1 mm thick) which have been spread across the build area using a counter-rotating powder leveling roller. The part building process takes place inside an enclosed chamber filled with nitrogen gas to minimize oxidation and degradation of the powdered material. The powder in the build platform is maintained at an elevated temperature just below the melting point and/or glass transition temperature of the powdered material. Infrared heaters are placed above the build platform to maintain an elevated temperature around the part being formed, as well as above the feed cartridges to preheat the powder prior to spreading over the build area. In some cases, the build platform is also heated using resistive heaters around the build platform. This preheating of powder and maintenance of an elevated, uniform temperature within the build platform are necessary to minimize the laser power requirements of the process (with preheating, less laser energy is required for fusion) and to prevent warping of the part during the build due to non-uniform thermal expansion and contraction (resulting in curling) [3–5].

Once an appropriate powder layer has been formed and preheated, a focused CO_2 laser beam is directed onto the powder bed and is moved using galvanometers in such a way that it thermally fuses the material to form the slice cross-section. Surrounding powder remains loose and serves as support for subsequent layers, thus eliminating the need for the secondary supports which are necessary for Vat Photopolymerization (VPP) processes. After completing a layer, the build platform is lowered by one layer thickness, and a new layer of powder is laid and leveled using the counter-rotating roller. The beam scans the subsequent slice cross-section. This process repeats until the complete part is built. A cool-down period is typically required to allow the parts to uniformly come to a low enough temperature that they can be handled and exposed to ambient temperature and atmosphere. If the parts and powder bed are prematurely exposed to ambient temperature and atmosphere, the powders may degrade in the presence of oxygen, and the parts may warp due to uneven thermal contraction. Finally, the parts are removed from the powder bed, loose powder is cleaned off the parts, and further finishing operations, if necessary, are performed.

5.2 Materials

In principle, all materials that can be melted and resolidified can be used in PBF processes. A brief survey of materials processed using PBF processes will be given here. More details can be found in subsequent sections.

5.2.1 Polymers and Composites

Thermoplastic materials are well-suited for powder bed processing because of their relatively low melting temperatures, low thermal conductivities, and low tendency for balling. Polymers in general can be classified as either a thermoplastic or a thermoset polymer. Thermoset polymers are typically not processed using PBF into parts, since PBF typically operates by melting particles to fabricate part cross-sections, but thermosets degrade, but do not melt, as their temperature is increased. Thermoplastics can be classified further in terms of their crystallinity. Amorphous polymers have a random molecular structure, with polymer chains randomly intertwined. In contrast, crystalline polymers have a regular molecular structure. Much more common are semi-crystalline polymers which have regions of regular structure, called crystallites, and regions of amorphous structure. Amorphous polymers melt over a fairly wide range of temperatures. As the crystallinity of a polymer increases, however, its melting characteristics tend to become more centered around a well-defined melting point.

At present, the most common material used in PBF is polyamide, a thermoplastic polymer, commonly known in the USA as nylon. Most polyamides have fairly high crystallinity and are classified as semi-crystalline materials. They have distinct melting points that enable them to be processed reliably. A given amount of laser energy will melt a certain amount of powder; the melted powder fuses and cools, forming part of a cross-section. In contrast, amorphous polymers tend to melt gradually, cool more slowly, and not form well-defined solidified features. In pLS, amorphous polymers tend to sinter into highly porous shapes, whereas crystalline polymers are typically processed using full melting, which result in higher densities. Polyamide 11 and polyamide 12 are commercially available, where the number designates the number of carbon atoms that are provided by one of the monomers that is reacted to produce polyamide. However, crystalline polymers exhibit greater shrinkage compared to amorphous materials and are more susceptible to curling and distortion and thus require more uniform temperature control. Mechanical properties of pLS parts produced using polyamide powders are similar to those of injection molded thermoplastic parts, but with significantly reduced elongation and unique microstructures.

Polystyrene-based materials with low residual ash content are particularly suitable for making sacrificial patterns for investment casting using pLS. Interestingly, polystyrene is an amorphous polymer but is a successful example material due to its intended application. Porosity in an investment casting pattern aids in melting out the pattern after the ceramic shell is created. Polystyrene parts intended for precision investment casting applications should be sealed to prevent ceramic material seeping in and to achieve a smooth surface finish.

Elastomeric thermoplastic polymers are available for producing highly flexible parts with rubber-like characteristics. These elastomers have good resistance to degradation at elevated temperatures and are resistant to chemicals like gasoline and automotive coolants. Elastomeric materials can be used to produce gaskets, industrial seals, shoe soles, and other components.

Additional polymers that are commercially available include flame-retardant polyamide and polyaryletherketone (known as PAEK or PEEK). Both 3D Systems and EOS GmbH offer most of the materials listed in this section.

Researchers have investigated quite a few polymers for biomedical applications. Several types of biocompatible and biodegradable polymers have been processed using pLS, including polycaprolactone (PCL), polylactide (PLA), and poly-L-lactide (PLLA). Composite materials consisting of PCL and ceramic particles, including hydroxyapatite and calcium silicate, have also been investigated for the fabrication of bone replacement tissue scaffolds.

In addition to neat polymers, polymers in PBF can have fillers that enhance their mechanical properties. For example, the Duraform material from 3D Systems is offered as Duraform PA, which is polyamide 12, as well as Duraform GF, which is polyamide 12 filled with small glass beads. The glass additive enhances the material's stiffness significantly but also causes its ductility to be reduced, compared to polyamide materials without fillers. Additionally, EOS GmbH offers aluminum particle, carbon fiber, and their own glass bead filled polyamide materials.

5.2.2 Metals and Composites

A wide range of metals has been processed using PBF. Generally, any metal that can be welded is considered to be a good candidate for PBF processing. Several types of steels, typically stainless and tool steels, titanium and its alloys, nickel-based alloys, some aluminum alloys, and cobalt-chrome have been processed and are commercially available in some form. Additionally, some companies offer PBF of precious metals, such as silver and gold.

Historically, a number of proprietary metal powders (either thermoplastic binder-coated or binder mixed) were developed before modern mLS machines were available. RapidSteel was one of the first metal/binder systems, developed by DTM Corp. The first version of RapidSteel was available in 1996 and consisted of a thermoplastic binder-coated 1080 carbon steel powder with copper as the infiltrant. RapidSteel achieved fusion using liquid-phase sintering of separate particles, whereas subsequent variants were coated particles, as described in Sect. 5.3.3.1 below. Parts produced using RapidSteel were debinded (350–450 °C), sintered (around 1000 °C), and finally infiltrated with Cu (1120 °C) to produce a final part with approximately 60% low carbon steel and 40% Cu. This is an example of liquid-phase sintering which will be described in the next section.

RapidSteel 2.0 powder was introduced in 1998 for producing functional tooling, parts and mold inserts for injection molding. It was a dry blend of 316 stainless steel powder impact milled with thermoplastic and thermoset organic binders with an average particle size of 33 μm. After green part fabrication, the part was debinded and sintered in a hydrogen-rich atmosphere. The bronze infiltrant was introduced in a separate furnace run to produce a 50% steel and 50% bronze composite. RapidSteel 2.0 was structurally more stable than the original RapidSteel material because the bronze infiltration temperature was less than the sintering temperature of the stainless steel powder. A subsequent material development was LaserForm ST-100, which had a broader particle size range, with fine particles not being screened out. These fine particles allowed ST-100 particles to be furnace sintered at a lower temperature than RapidSteel 2.0, making it possible to carry out sintering and infiltration in a single furnace run. In addition to the above, H13 and A6 tool steel powders with a polymer binder can also be used for tooling applications. The furnace processing operations (sintering and infiltration) must be carefully designed with appropriate choices of temperature, heating and cooling rates, furnace atmosphere pressure, amount of infiltrant, and other factors, to prevent excessive part distortion. After infiltration, the part is finish machined as needed. These issues are further explored in the post-processing chapter.

Several proprietary metal powders were marketed by EOS for their M250 Xtended metal platforms, prior to the introduction of modern mLS machines. These included liquid-phase sintered bronze-based powders and steel-based powders and other proprietary alloys (all without polymer binders). These were suitable for producing tools and inserts for injection molding of plastics. Parts made from these powders were often infiltrated with epoxy to improve the surface finish and seal porosity in the parts. Proprietary Ni-based powders for direct tooling applications and Cu-based powders for parts requiring high thermal and electrical conductivities were also available. All of these materials have been successfully used by many organizations; however, the more recent introduction of mLS and Electron Beam Powder Bed Fusion (EB-PBF) (which is known by electron beam melting (EBM) by Arcam) technology has made these alloys obsolete, as engineering-grade alloys are now able to be processed using a number of manufacturers' machines.

As mentioned, titanium alloys, numerous steel alloys, nickel-based super alloys, CoCrMo, and more are widely available from numerous manufacturers. It should be noted that alloys that crack under high solidification rates are not good candidates for mLS. Due to the high solidification rates in mLS, the crystal structures produced and mechanical properties are different than those for other manufacturing processes. These structures may be metastable, and the heat treatment recipes needed to produce standard microstructures may be different. As mLS and EB-PBF processes advance, the types of metal alloys which are commonly utilized will grow, and new alloys specifically tailored for PBF production have been developed.

5.2.3 Ceramics and Ceramic Composites

Ceramic materials are generally described as compounds that consist of metal oxides, carbides, nitrides and their combinations. Several ceramic materials are available commercially including aluminum oxide and titanium oxide. Commercial machines were developed by a company called Phenix Systems in France, which was acquired by 3D Systems in 2013. At the time of publication, these machines have been discontinued, but we expect other manufacturers to introduce ceramic laser sintering machines in the future.

Ceramics and metal–ceramic composites have been demonstrated in research. Typically, ceramic precipitates form through reactions occurring during the sintering process. One example is the processing of aluminum in a nitrogen atmosphere, which forms an aluminum matrix with small regions of AlN interspersed throughout. This process is called chemically induced sintering and is described further in the next section.

Biocompatible materials have been developed for specific applications. For example, calcium hydroxyapatite, a material very similar to human bone, has been processed using pLS for medical applications.

5.3 Powder Fusion Mechanisms

Since the introduction of LS, each new PBF technology developer has introduced competing terminology to describe the mechanism by which fusion occurs, with variants of "sintering" and "melting" being the most popular. A list of historical terminology for various PBF technologies is shown in Table 5.1 as a reference.

The use of a single word to describe powder fusion is inherently problematic as multiple mechanisms are possible. There are four different fusion mechanisms which are present in PBF processes [6]. These include solid-state sintering, chemically induced binding, liquid-phase sintering, and full melting. Most commercial processes utilize liquid-phase sintering and melting. A brief description of each of these mechanisms and their relevance to AM is as follows.

Table 5.1 Different technologies and commercial names for PBF systems

Terminology	Manufacturer	Acronym
Ceramic laser sintering	NA	CLS
Direct metal laser melting	GE	DMLM
Direct metal laser sintering	EOS GmbH Electro Optical Systems [7]	DMLS
Direct metal laser forming	NA	DMLF
Direct metal printing	NA	DMP
Electron beam melting	GE former name (Arcam)	EBM
LaserCUSISNG	GE former name (Concept Laser)	LaserCUSING
Laser metal fusion	NA	LMF
Laser sintered in solid phase	3D Systems former name (Phenix Systems)	LSSP
Powder Bed Fusion	Trumpf [8]	PBF
Selective laser melting	SLM Solutions, Renishaw, DMG MORI (Former name Realizer)	SLM
Selective laser reaction sintering	3D Systems former name DTM	SLRS
Selective Laser Sintering	3D Systems former name DTM	SLS

5.3.1 Solid-State Sintering

The use of the word sintering to describe powder fusion as a result of thermal processing predates the advent of AM. Sintering, in its classical sense, indicates the fusion of powder particles without melting (i.e., in their "solid-state") at elevated temperatures. This occurs at temperatures between one half of the absolute melting temperature and the melting temperature. The driving force for solid-state sintering is the minimization of total free energy, E_s, of the powder particles. The mechanism for sintering is primarily diffusion between powder particles.

Surface energy E_s is proportional to total particle surface area S_A, through the equation $E_s = \gamma_s \times S_A$ (where γ_s is the surface energy per unit area for a particular material, atmosphere, and temperature). When particles fuse at elevated temperatures (see Fig. 5.2), the total surface area decreases, and thus surface energy decreases.

As the total surface area of the powder bed decreases, the rate of sintering slows. To achieve very low porosity levels, long sintering times or high sintering temperatures are required. The use of external pressure, as is done with hot isostatic pressing, increases the rate of sintering.

As total surface area in a powder bed is a function of particle size, the driving force for sintering is directly related to the surface area to volume ratio for a set of particles. The larger the surface area to volume ratio, the greater the free-energy driving force. Thus, smaller particles experience a greater driving force for necking and consolidation, and hence, smaller particles sinter more rapidly and initiate sintering at lower temperature than larger particles.

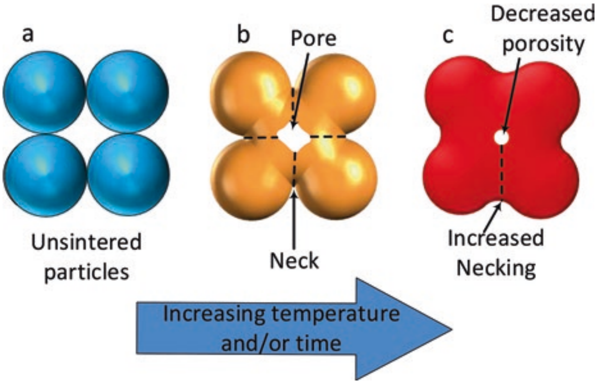


Fig. 5.2 Solid-state sintering. (**a**) Closely packed particles prior to sintering. (**b**) Particles agglomerate due to diffusion at temperatures above one half of the absolute melting temperature, as they seek to minimize free energy by decreasing surface area. (**c**) As sintering progresses, neck size increases and pore size decreases

As diffusion rates exponentially increase with temperature, sintering becomes increasingly rapid as temperatures approach the melting temperature, which can be modeled using a form of the Arrhenius equation. However, even at temperatures approaching the melting temperature, diffusion-induced solid-state sintering is the slowest mechanism for selectively fusing regions of powder within a PBF process.

For AM, the shorter the time it takes to form a layer, the more economically competitive the process becomes. Thus, the heat source which induces fusion should move rapidly and/or induce fusion quickly to increase build rates. Since the time it takes for fusion by sintering is typically much longer than for fusion by melting, few AM processes use sintering as a primary fusion mechanism.

Sintering, however, is still important in most thermal powder processes, even if sintering is not the primary fusion mechanism. There are three secondary ways in which sintering affects a build:

- If the loose powder within the build platform is held at an elevated temperature, the powder bed particles will begin to sinter to one another. This is typically considered a negative effect, as agglomeration of powder particles means that each time the powder is recycled the average particle size increases. This changes the spreading and melting characteristics of the powder each time it is recycled. One positive effect of loose powder sintering, however, is that the powder bed will gain a degree of tensile and compressive strength, thus helping to minimize part curling.
- As a part is being formed in the build platform, thermally induced fusion of the desired cross-sectional geometry causes that region of the powder bed to become much hotter than the surrounding loose powder. If melting is the dominant fusion mechanism (as is typically the case), then the just-formed part cross-section will be quite hot. As a result, the loose powder bed immediately surrounding the fused region heats up considerably, due to conduction from the part being formed.

This region of powder may remain at an elevated temperature for a long time (many hours for polymers) depending upon the size of the part being built, the heater and temperature settings in the process, and the thermal conductivity of the powder bed. Thus, there is sufficient time and energy for the powder immediately next to the part being built to fuse significantly due to solid-state sintering, both to itself and to the part. This results in "part growth," where the originally scanned part grows a "skin" of increasing thickness the longer the powder bed is maintained at an elevated temperature. This phenomenon can be seen in Fig. 5.3 as unmolten particles fused to the edge of a part. For many materials, the skin formed on the part goes from high density, low porosity near the originally scanned region to lower density, and higher porosity further from the part. This part growth can be compensated in the build planning stage by offsetting the laser beam to compensate for part growth or by offsetting the surface of the STL model. In addition, different post-processing methods will remove this skin to a different degree. Thus, the dimensional repeatability of the final part is highly dependent upon effectively compensating for and controlling this part growth. Performing repeatable post-processing to remove the same amount of the skin for every part is thus quite important.

- Rapid fusion of a powder bed using a laser or other heat source makes it difficult to achieve 100% dense, porosity-free parts. Thus, a feature of many parts built using PBF techniques (especially for polymers) is distributed porosity throughout the part. This is typically detrimental to the intended part properties. However, if the part is held at an elevated temperature after scanning, solid-state sintering combined with other high-temperature phenomena (such as grain growth in metals) causes the % porosity in the part to decrease. Since lower layers are maintained at an elevated temperature while additional layers are added, this can result in lower regions of a part being denser than upper regions of a part. This uneven porosity can be controlled, to some extent, by carefully controlling the

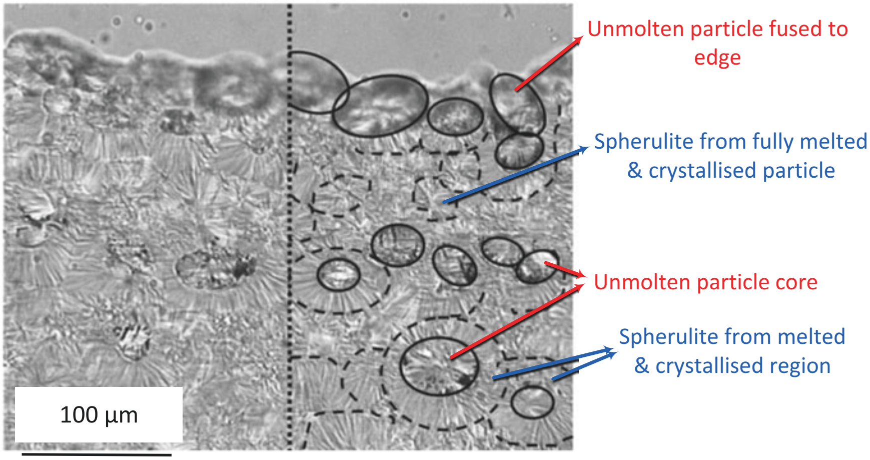


Fig. 5.3 Typical pLS microstructure for nylon polyamide (Elsevier license number 4720630952538) [9]

part bed temperature, cooling rate, and other parameters. Electron beam melting, in particular, often makes use of the positive aspects of elevated-temperature solid-state sintering and grain growth by purposefully maintaining the metal parts that are being built at a high enough temperature that diffusion and grain growth cause the parts being built to reach 100% density.

5.3.2 Chemically Induced Sintering

Chemically induced sintering involves the use of thermally activated chemical reactions between two types of powders or between powders and atmospheric gases to form a by-product which binds the powders together. This fusion mechanism is primarily utilized for ceramic materials. Examples of reactions between powders and atmospheric gases include laser processing of SiC in the presence of oxygen, whereby SiO_2 forms and binds together a composite of SiC and SiO_2; laser processing of ZrB_2 in the presence of oxygen, whereby ZrO_2 forms and binds together a composite of ZrB_2 and ZrO_2; and laser processing of Al in the presence of N_2, whereby AlN forms and binds together the Al and AlN particles.

For chemically induced sintering between powders, various research groups have demonstrated that mixtures of high-temperature structural ceramic and/or intermetallic precursor materials can be made to react using a laser. In this case, raw materials which exothermically react to form the desired by-product are premixed and heated using a laser. By adding chemical reaction energy to the laser energy, high-melting-temperature structures can be created at relatively low-laser energies.

One common characteristic of chemically induced sintering is part porosity. As a result, post-process infiltration or high-temperature furnace sintering to higher densities is often needed to achieve properties that are useful for most applications. This post-process infiltration may involve other reactive elements, forming new chemical compounds after infiltration. The cost and time associated with post-processing have limited the adoption of chemically induced sintering in commercial machines.

5.3.3 Liquid-Phase Sintering and Partial Melting

Liquid-phase sintering (LPS)is arguably the most versatile mechanism for PBF. Liquid-phase sintering is a term used extensively in the powder processing industry to refer to the fusion of powder particles when a portion of constituents within a collection of powder particles becomes molten, while other portions remain solid. In LPS, the molten constituents act as the glue which binds the solid particles together. As a result, high-temperature particles can be bound together without needing to melt or sinter those particles directly. LPS is used in traditional powder metallurgy to form, for instance, cemented carbide cutting tools where Co is used as the lower-melting-point constituent to glue together particles of WC.

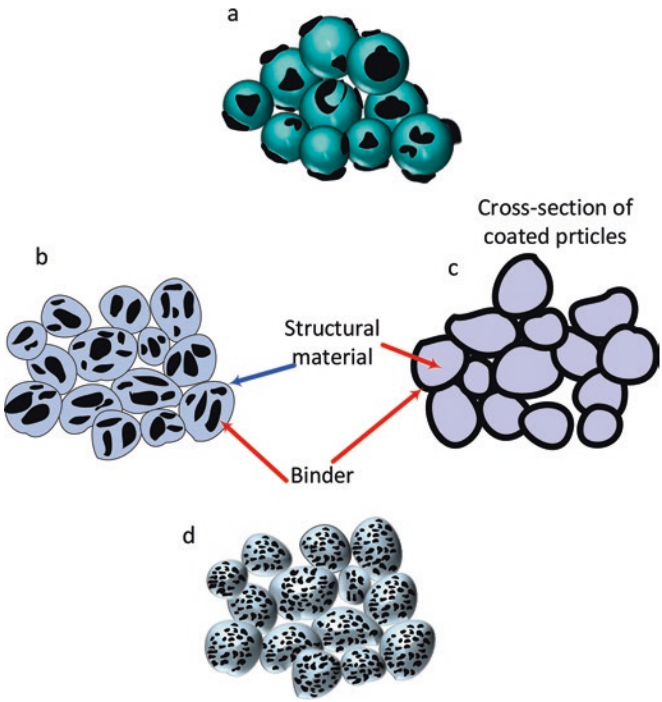


Fig. 5.4 Liquid-phase sintering variations used in PBF processing: (**a**) separate particles, (**b**) composite particles, (**c**) coated particles, and (**d**) indistinct mixtures. Darker regions represent the lower-melting-temperature binder material. Lighter regions represent the high-melting-temperature structural material. For indistinct mixtures, microstructural alloying eliminates distinct binder and structural regions

There are many ways in which LPS can be utilized as a fusion mechanism in AM processes. For purposes of clarity, the classification proposed by Kruth et al. [6] has formed the basis for the distinctions discussed in the following section and shown in Fig. 5.4.

5.3.3.1 Distinct Binder and Structural Materials

In many LPS situations, there is a clear distinction between the binding material and the structural material. The binding and structural material can be combined in three different ways: as separate particles, as composite particles, or as coated particles.

Separate Particles

A simple, well-mixed combination of binder and structural powder particles is sufficient in many cases for LPS. In cases where the structural material has the dominant properties desired in the final structure, it is advantageous for the binder material to be smaller in particle size than the structural material. This enables more efficient packing in the powder bed and less shrinkage and lower porosity after binding. The dispersion of smaller-particle-size binder particles around structural particles also helps the binder flow into the gaps between the structural particles more effectively, thus resulting in better binding of the structural particles. This is often true when, for instance, LS is used to process steel powder with a polymer binder (as discussed more fully in Sect. 5.3.5). This is also true when metal–metal mixtures and metal–ceramic mixtures are directly processed without the use of a polymer binder.

In the case of LPS of separate particles, the heat source passes by quickly, and there is typically insufficient time for the molten binder to flow and surface tension to draw the particles together prior to resolidification of the binder unless the binder has a particularly low viscosity. Thus, composite structures formed from separate particles typically are quite porous. This is often the intent for parts made from separate particles, which are then post-processed in a furnace to achieve the final part properties. Parts held together by polymer binders which require further post-processing (e.g., to lower or fill the porosity) are known as "green" parts.

In some cases, the density of the binder and structural material is quite different. As a result, the binder and structural material may separate during handling. In addition, some powdered materials are most economically manufactured at particle sizes that are too small for effective powder dispensing and leveling (see Sect. 5.5). In either case, it may be beneficial for the structural and/or binder particles to be bound together into larger particle agglomerates. By doing so, composite powder particles made up of both binder and structural material are formed.

Composite Particles

Composite particles contain both the binder and structural material within each powder particle. Mechanical alloying of binder and structural particles or grinding of cast, extruded, or molded mixtures into a powder results in powder particles that are made up of binder and structural materials agglomerated together. The benefits of composite particles are that they typically form higher density green parts and typically have better surface finish after processing than separate particles [6].

Composite particles can consist of mixtures of polymer binders with higher melting point polymer, metal or ceramic structural materials, or metal binders with higher melting point metal or ceramic structural materials. In all cases, the binder and structural portions of each particle, if viewed under a microscope, are distinct from each other and clearly discernable. The most common commercially available composite particle used in PBF processes is glass-filled nylon. In this case, the structural material (glass beads) is used to enhance the properties of the binding material (nylon) rather than the typical use of LPS where the binder is simply a necessary glue to help hold the structural material together in a useful geometric form.

Coated Particles

In some cases, a composite formed by coating structural particles with a binder material is more effective than random agglomerations of binder and structural materials. These coated particles can have several advantages including better absorption of laser energy, more effective binding of the structural particles, and better flow properties.

When composite particles or separate particles are processed, the random distribution of the constituents means that impinging heat energy, such as laser radiation, will be absorbed by whichever constituent has the highest absorptivity and/or most direct "line of sight" to the impinging energy. If the structural materials have a higher absorptivity, a greater amount of energy will be absorbed in the structural particles. If the rate of heating of the structural particles significantly exceeds the rate of conduction to the binder particles, the higher-melting-temperature structural materials may melt prior to the lower-melting-temperature binder materials. As a result, the anticipated microstructure of the processed material will differ significantly from one where the binder had melted, and the structural material had remained solid. This may, in some instances, be desirable but is typically not the intent when formulating a binder/structural material combination. Coated particles can help overcome the structural material heating problem associated with random constituent mixtures and agglomerates. If a structural particle is coated with the binder material, then the impinging energy must first pass through the coating before affecting the structural material. As melting of the binder and not the structural material is the objective of LPS, this helps ensure that the proper constituent melts.

Other benefits of coated particles exist. Since there is a direct correlation between the speed of the impinging energy in AM processing and the build rate, it is desirable for the binder to be molten for only a very short period of time. If the binder is present at the surfaces of the structural material, this is the most effective location for gluing adjacent particles together. If the binder is randomly mixed with the structural materials, and/or the binder's viscosity is too high to flow to the contact points during the short time it is molten, then the binder will not be as effective. As a result, the binder % content required for effective fusion of coated particles is usually less than the binder content required for effective fusion of randomly mixed particles.

Many structural metal powders are spherical. Spherical powders are easier to deposit and smooth using powder spreading techniques. Coated particles retain the spherical nature of the underlying particle shape and thus can be easier to handle and spread.

5.3.3.2 Indistinct Binder and Structural Materials

In polymers, due to their low thermal conductivity, it is possible to melt smaller powder particles and the outer regions of larger powder particles without melting the entire structure (see Fig. 5.3). Whether to more properly label this phenomenon

LPS or just “partial melting” is a matter of debate. Also with polymers, fusion can occur between polymer particles above their glass transition temperature but below their melting temperature. Similarly, amorphous polymers have no distinct melting point, becoming less viscous the higher the temperature goes above the glass transition temperature. As a result, in each of these cases, there can be fusion between polymer powder particles in cases where there is partial but not full melting, which falls within the historical scope of the term “liquid-phase sintering.”

In metals, LPS can occur between particles where no distinct binder or structural materials are present. This is possible during partial melting of a single particle type or when an alloyed structure has lower-melting-temperature constituents. For non-eutectic alloy compositions, melting occurs between the liquidus and solidus temperature of the alloy, where only a portion of the alloy will melt when the temperature is maintained in this range. Regions of the alloy with higher concentrations of the lower-melting-temperature constituent(s) will melt first. As a result, it is commonly observed that many metal alloys can be processed in such a way that only a portion of the alloy melts when an appropriate energy level is applied. This type of LPS of metal alloys was the method used in the early EOS M250 direct metal laser sintering machines. Subsequent metal laser sintering commercialized processes are all designed to fully melt the metal alloys they process.

5.3.4 Full Melting

Full melting is the mechanism most commonly associated with PBF processing of engineering metal alloys and semi-crystalline polymers. In these materials, the entire region of material subjected to impinging heat energy is melted to a depth exceeding the layer thickness. Thermal energy of subsequent scans of a laser or electron beam (next to or above the just-scanned area) is typically sufficient to remelt a portion of the previously solidified solid structure; and thus, this type of full melting is very effective at creating well-bonded, high-density structures from engineering metals and polymers.

The most common material used in PBF processing is nylon polyamide [10, 11]. As a semi-crystalline material, it has a distinct melting point. In order to produce parts with the highest possible strength, these materials should be fully melted during processing. However, elevated temperatures associated with full melting result in part growth, and thus, for practical purposes, many accuracy versus strength optimization studies result in parameters which are at the threshold between full melting and LPS, as can be seen from Fig. 5.3.

For metal PBF processes, the engineering alloys that are utilized in these machines (Ti, stainless steel, CoCr, etc.) are typically fully melted. The rapid melting and solidification of these metal alloys result in unique properties that are distinct from and can sometime be more desirable than cast or wrought parts made from identical alloys.

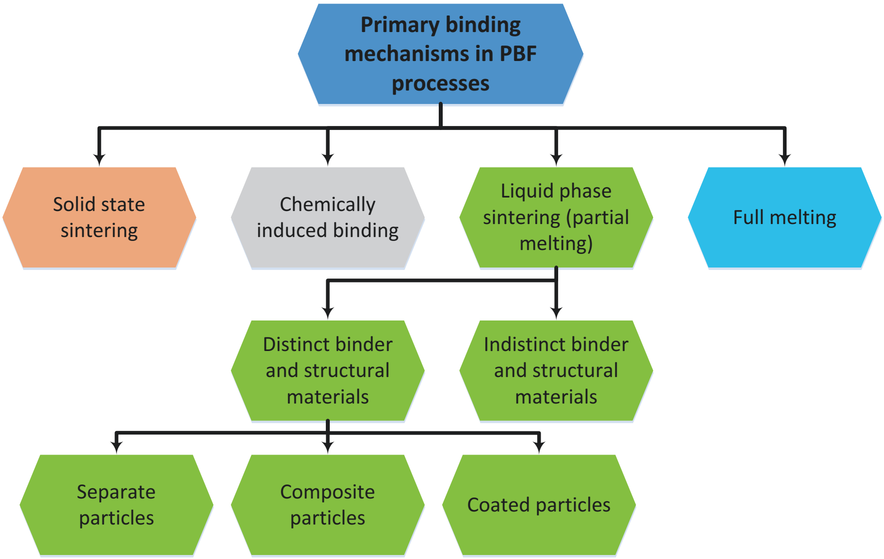


Fig. 5.5 Primary binding mechanisms in PBF processes. (Adapted from [6])

Figure 5.5 summarizes the various binding mechanisms which are utilized in PBF processes. Regardless of whether a technology is known as "Selective Laser Sintering," "selective laser melting," "direct metal laser sintering," "LaserCUSING," "electron beam melting," or some other name, it is possible for any of these mechanisms to be utilized (and, in fact, often more than one is present) depending upon the powder particle combinations and energy input utilized to form a part [12, 13].

5.3.5 High-Speed Sintering

High-speed sintering (HSS) is a PBF technology that utilizes the benefits of inkjet printing to form a composite structure of the spread powder and the printed ink as the cross-section. As opposed to Binder Jetting (BJT) technology, where the ink glues the powder particles together, in HSS, the ink acts as a heat absorption enhancer. After printing, a heater is run across the surface of the powder bed. Wherever ink has been printed, the amount of heat absorbed is sufficient to cause fusion between adjacent particles. Wherever ink is not printed, the reflectivity of the powder remains high enough that absorbed energy is too low to fuse powders.

HSS is being developed and commercialized by a number of companies. Most notable are the HSS processes developed by Xaar and Voxeljet as well as the MultiJet Fusion (MJF) process from Hewlett–Packard. These technologies are opening up new opportunities for functionality and flexibility in AM applications. By combining the advantages of both PBF and BJT, they can achieve the bonding strength of sintering at the speed of BJT. The benefit of combining industrial inkjet technology with a simple heating step is that it offers high precision build rates with consistent layer timing.

Most HSS processes follow a similar build methodology. The process starts by depositing a fine layer of loose powder on the build platform. An inkjet print head then moves over the powder and according to the designed shape prints infrared light-absorbing ink (Fig. 5.6a, b). The entire build area is then irradiated with infrared light causing the printed region to absorb sufficient energy to fuse the underlying powder (Fig. 5.6c). After this process the build platform is lowered one layer thickness. This process is repeated layer-by-layer until the build is complete, and the sintered block is then cooled down before part removal. In contrast to laser-based processes, the entire building process for each layer can be printed in a single pass which provides a constant layer time, regardless of the complexity and size of the components. Commercial print heads have a high resolution, and large arrays of individually controllable nozzles enable printing across the entire powder bed simultaneously. This method is typically performed in air rather than in a controlled build chamber atmosphere, which reduces the cost of the process. Complex elastic and functional models can be created using different polymers such as PA12 or TPU. Figure 5.6 shows the schematic of the HSS process.

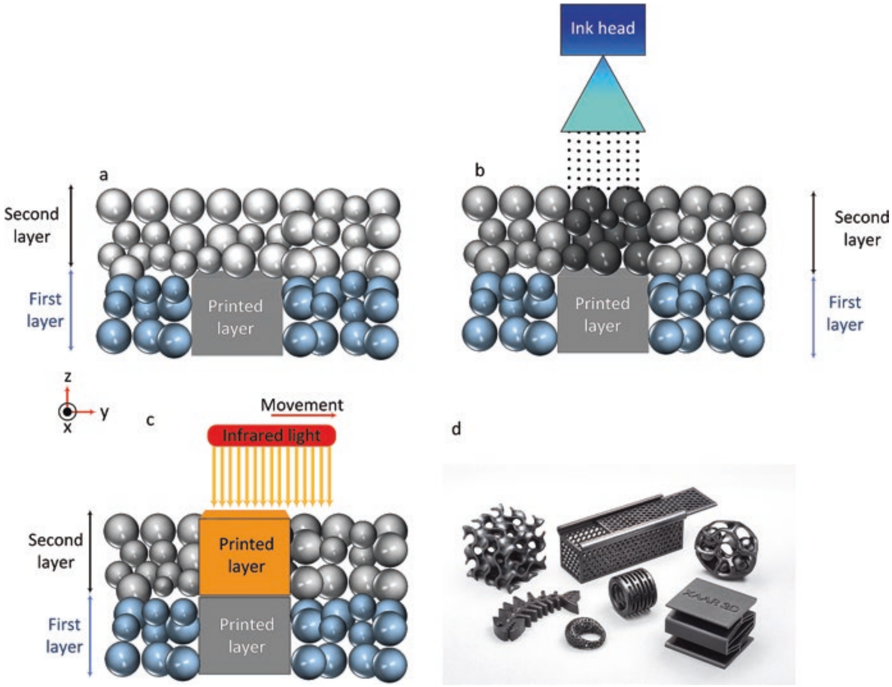


Fig. 5.6 Schematic of HSS process (**a**) loose powder above a previously printed layer, (**b**) adding ink, (**c**) infrared irradiation, and (**d**) 3D printed parts for industrial applications: post-processed and dyed black. Produced by Xaar 3D. (Photo courtesy of Xaar 3D)

5.4 Metal and Ceramic Part Fabrication

5.4.1 Metal Parts

There are four common approaches for using PBF processes in the creation of complex metal components: full melting, liquid-phase sintering, indirect processing, and pattern methods. In the full melting and liquid-phase sintering (when metals are used as both the high-temperature and low-temperature constituents) approaches, a metal part is typically usable in the state in which it comes out of the machine, after separation from a build plate.

In indirect processing, a polymer-coated metallic powder or a mixture of metallic and polymer powders (as described in Sect. 5.3.3.1 above) is used for part construction. Figure 5.7 shows the steps involved in indirect processing of metal powders. During indirect processing, the polymer binder is melted and binds the particles together, and the metal powder remains solid. The metallic powder particles remain

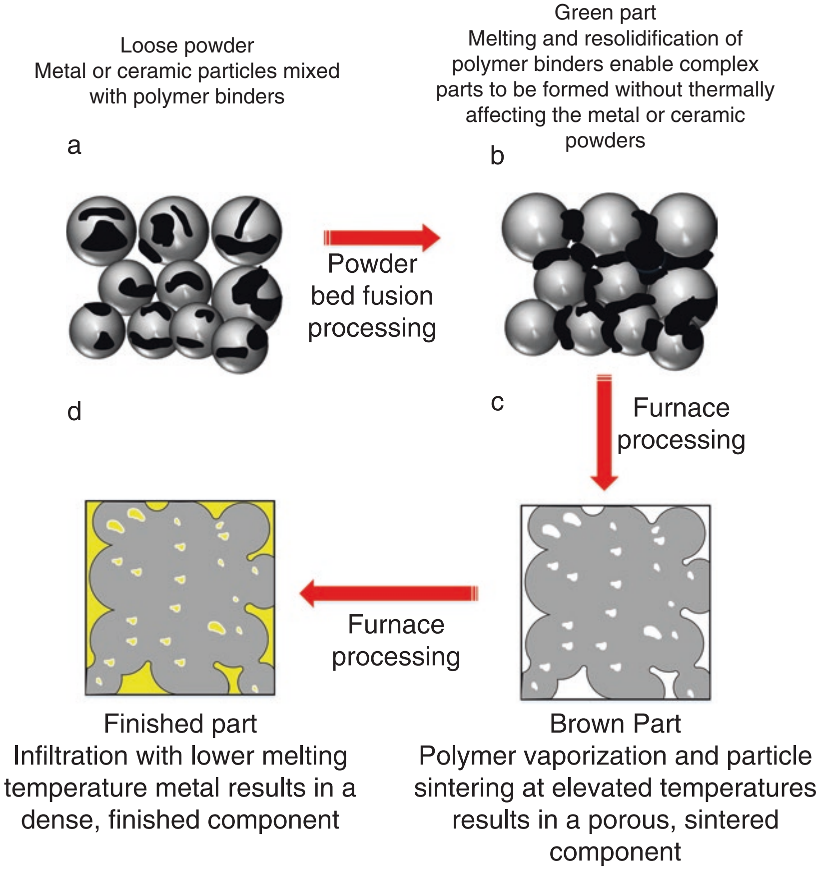


Fig. 5.7 Indirect processing of metal and ceramic powders using PBF

largely unaffected by the heat of the laser, whereas the binder melts and flows to regions between the metal powders due to capillary action. The parts produced are generally porous (sometimes exceeding 50 vol.% porosity). The polymer-bound green parts are subsequently furnace processed. Furnace processing occurs in two stages: (1) debinding and (2) infiltration or consolidation. During debinding, the polymer binder is vaporized to remove it from the green part. Typically, the temperature is also raised to the extent that a small degree of necking (sintering) occurs between the metal particles. Subsequently, the remaining porosity is either filled by infiltration of a lower-melting-point metal to produce a fully dense metallic part or by further sintering and densification to reduce the part porosity. Infiltration is easier to control, dimensionally, as the overall shrinkage is much less than during consolidation. However, infiltrated structures are always composite in nature, whereas consolidated structures can be made up of a single-material type.

The last approach to metal part creation using PBF is the pattern approach. For the previous three approaches, metal powder is utilized in the PBF process; but in this final approach, the part created in the PBF process is a pattern used to create the metal part. The two most common ways PBF-created parts are utilized as patterns for metal part creation are as investment casting patterns or as sand-casting molds. In the case of investment casting, polystyrene or wax-based powders are used in the machine, subsequently invested in ceramic during post-processing, and melted out during casting. In the case of sand-casting molds, mixtures of sand and a thermosetting binder are directly processed in the machine to form a sand-casting core, cavity, or insert. These molds are then assembled, and molten metal is cast into the mold, creating a metal part. Both indirect and pattern-based processes are further discussed in Chap. 20.

5.4.2 Ceramic Parts

Similar to metal parts, there are a number of ways that PBF processes are utilized to create ceramic parts. These include direct sintering, chemically induced sintering, indirect processing, and pattern methods. In direct sintering, a high temperature is maintained in the powder bed, and a laser is utilized to accelerate sintering of the powder bed in the prescribed location of each layer. The resultant ceramic parts will be quite porous and thus are often post-processed in a furnace to achieve higher density. This high porosity is also seen in chemically induced sintering of ceramics, as described earlier.

Indirect processing of ceramic powders is identical to indirect processing of metal powders (Fig. 5.7). After debinding, the ceramic brown part is consolidated to reduce porosity or is infiltrated. In the case of infiltration, when metal powders are used as the infiltrant, a ceramic–metal composite structure can be formed. In some cases, such as when creating SiC structures, a polymer binder can be selected, which leaves behind a significant amount of carbon residue within the brown part. Infiltration with molten Si will result in a reaction between the molten Si and the remaining carbon to produce more SiC, thus increasing the overall SiC content and reducing the fraction of metal Si in the final part. These related approaches have been used to form interesting ceramic–matrix composites and ceramic–metal structures for a number of different applications.

5.5 Process Parameters and Analysis

The use of optimum process parameters is extremely important for producing satisfactory parts using PBF processes. In this section, we will discuss “laser” processing and parameters, but by analogy the parameters and models discussed below could also be applied to other thermal energy sources, such as electron beams or infrared heaters.

5.5.1 Process Parameters

In PBF, process parameters can be lumped into four categories: (1) laser-related parameters (laser power, spot size, pulse duration, pulse frequency, etc.), (2) scan-related parameters (scan speed, scan spacing, and scan pattern), (3) powder-related parameters (particle shape, size and distribution, powder bed density, layer thickness, material properties, etc.), and (4) temperature-related parameters (powder bed temperature, powder feeder temperature, temperature uniformity, etc.). It should be noted that most of these parameters are strongly interdependent and are mutually interacting. The required laser power, for instance, typically increases with melting point of the material and lower powder bed temperature and also varies depending upon the absorptivity characteristics of the powder bed, which is influenced by material type and powder shape, size, and packing density.

A typical PBF machine includes two galvanometers (one for the x-axis and one for the y-axis motion). Similar to stereolithography, scanning often occurs in two modes, contour mode and fill mode, as shown in Fig. 5.8. In contour mode, the outline of the part cross-section for a particular layer is scanned. This is typically done for accuracy and surface finish reasons around the perimeter. The rest of the cross-section is then scanned using a fill pattern. A common fill pattern is a rastering technique whereby one axis is incrementally moved a laser scan width, and the other axis is continuously swept back and forth across the part being formed. In some cases the fill section is subdivided into stripes (where each stripe is scanned sequentially and the stripe angle is rotated every layer) or squares (with each square being processed separately). Randomized scanning is sometimes utilized so that there is no preferential direction for residual stresses induced by the scanning. The use of stripes or a square-based (chessboard) strategy is primarily for metal parts, whereas a simple raster pattern for the entire part (without subdividing into stripes or squares) is typically used for polymers and other low-temperature processing.

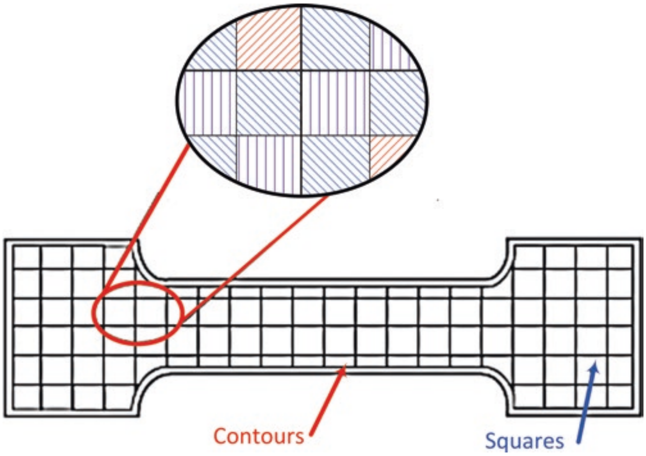


Fig. 5.8 Scan strategies employed in PBF techniques

In addition to melt pool characteristics, scan pattern and scan strategy can have a profound impact on residual stress accumulation within a part. For instance, if a part is moved from one location to another within a machine, the exact laser paths to build the part may change. These laser path changes may cause the part to distort more in one location than another. Thus it is possible for a part to build successfully in one location but not in another location in the same machine due simply to how the scan strategy is applied in different locations.

Powder shape, size, and size distribution strongly influence laser absorption characteristics as well as powder bed density, powder bed thermal conductivity, and powder spreading. Finer particles provide greater surface area and absorb laser energy more efficiently than coarser particles. Powder bed temperature, laser power, scan speed, and scan spacing must be balanced to provide the best trade-off between melt pool size, dimensional accuracy, surface finish, build rate, and mechanical properties. The powder bed temperature should be kept uniform and constant to achieve repeatable results. Generally, high-laser-power/high-bed-temperature combinations produce dense parts but can result in part growth, poor recyclability, and difficulty cleaning parts. On the other hand, low-laser-power/low-bed-temperature combinations produce better dimensional accuracy, but result in lower density parts and a higher tendency for layer delamination. High-laser-power and low-part-bed-temperatures result in an increased tendency for non-uniform shrinkage and the buildup of residual stresses, leading to curling of parts.

Laser power, spot size and scan speed, and bed temperature together determine the energy input needed to fuse the powder into a useable part. The longer the laser dwells in a particular location, the deeper the fusion depth and the larger the melt pool diameter. Typical layer thicknesses range from 0.02 to 0.15 mm. Operating at lower laser powers requires the use of lower scan speeds in order to ensure proper particle fusion. Melt pool size is highly dependent upon settings of laser power, scan speed, spot size, and bed temperature. Scan spacing should be selected to ensure a sufficient degree of melt pool overlap between adjacent lines of fused material to ensure robust mechanical properties.

The powder bed density, as governed by powder shape, size, distribution, and spreading mechanism, can strongly influence the part quality. Powder bed densities typically range between 50% and 60% for most commercially available powders but may be as low as 30% for irregular ceramic powders. Generally the higher the powder packing density, the higher the bed thermal conductivity and the better the part mechanical properties.

Most commercialized PBF processes use continuous wave (CW) lasers. Laser processing research with pulsed lasers, however, has demonstrated a number of potential benefits over CW lasers. In particular, the tendency of molten metal to form disconnected balls of molten metal, rather than a flat molten region on a powder bed surface, can be partially overcome by pulsed energy. CW laser processing is faster than pulsed laser processing, so most machines are configured to use CW lasers to increase machine productivity.

5.5.2 Applied Energy Correlations and Scan Patterns

Many common physics, thermodynamics, and heat transfer models are relevant to PBF techniques. In particular, solutions for stationary and moving point heat sources in infinite media and homogenization equations (to estimate, for instance, powder bed thermophysical properties based upon powder morphology, packing density, etc.) are commonly utilized. The solidification modeling discussed in the Directed Energy Deposition (DED) chapter (Chap. 10) can also be applied to PBF processes. For the purposes of this chapter, a highly simplified model which estimates the energy input characteristics of PBF processes is introduced and discussed with respect to process optimization for PBF processes.

Melt pool formation and characteristics are primarily determined by the total amount of applied energy which is absorbed by the powder bed as the laser beam passes. There is a difference between energy input and absorbed energy, so it is important to make a distinction between the two cases. Input energy is related to heat source power, speed of translation of the heat source, and area of the heat source energy (e.g., diameter of the beam), while absorbed energy is a function of heat source power, speed, diameter of the beam, layer thickness, hatch distance, absorptivity of the material, thermophysical properties of the material, etc. Therefore, it is important to clarify which sort of energy density is discussed.

Both the melt pool size and melt pool depth are a function of absorbed energy density. A simplified energy density equation has been used by numerous investigators as a simple method for correlating input process parameters to the density and strength of produced parts [14]. In their simplified model, applied energy density E_{A} (also known as the Andrews number) can be found using (5.1):

$$E_{\mathrm{A}} = \frac{P}{\mathrm{SS} \times \mathrm{HS}} \tag{5.1}$$

where P is laser power, SS is scan speed, and HS is the scan spacing/hatch spacing between parallel scan lines. In this simplified model, applied energy increases with increasing laser power and decreases with increasing velocity and scan spacing. For pLS, typical scan spacing values are ~100 μm, whereas typical laser spot sizes are ~300 μm. Thus, typically every point is scanned by multiple passes of the laser beam.

Although (5.1) does not include powder absorptivity, heat of fusion, laser spot size, bed temperature, or other important characteristics, it provides the simplest analytical approach for optimizing machine performance for a material. For a given material, laser spot size, and machine configuration, a series of experiments can be run to determine the minimum applied energy necessary to achieve adequate material fusion for the desired material properties. Subsequently, build speed can be maximized by utilizing the fastest combination of laser power, scan rate, and scan spacing for a particular machine architecture based upon (5.1).

Optimization of build speed using applied energy is reasonably effective for PBF of polymer materials. However, when a molten pool of metal is present on a powder bed, a phenomenon called balling often occurs. When surface tension forces overcome a combination of dynamic fluid, gravitational, and adhesion forces, the molten metal will form a ball. The surface energy driving force for metal powders to limit their surface area to volume ratio (which is minimized as a sphere) is much greater than the driving force for polymers, and thus this phenomenon is unimportant for polymers but critically important for metals. An example of balling tendency at various power and scan speed combinations is shown in Fig. 5.9 [15]. This figure illustrates five typical types of tracks which are formed at various process parameter combinations.

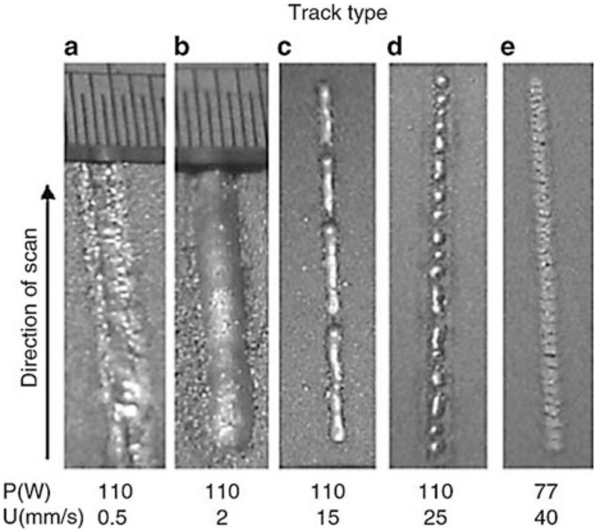
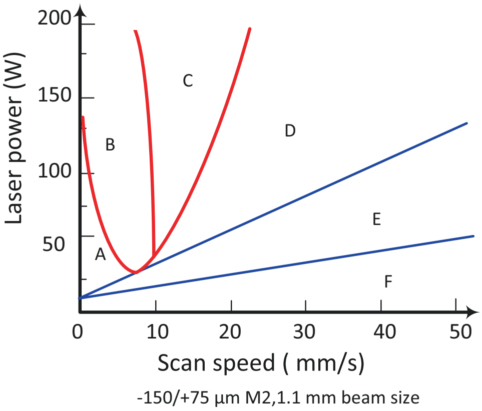


Fig. 5.9 Five examples of test tracks made in −150/+75 μm M2 steel powder in an argon atmosphere with a CO_2 laser beam of 1.1 mm spot size, at similar magnifications. (© Professional Engineering Publishing, reproduced from Childs et al. [15])

Fig. 5.10 Process map for track types. (© Professional Engineering Publishing, reproduced from Childs et al. [15])



A process map showing regions of power and scan speed combinations which result in each of these track types is shown in Fig. 5.10. As described by Childs et al., tracks of type A were continuous and flat topped or slightly concave. At slightly higher speeds, type B tracks became rounded and sank into the bed. As the speed increased, type C tracks became occasionally broken, although not with the regularity of type D tracks at higher speeds, whose regularly and frequently broken tracks are perfect examples of the balling effect. At even higher speeds, fragile tracks were formed (type E) where the maximum temperatures exceed the solidus temperature but do not reach the liquidus temperature (i.e., partially melted or liquid-phase sintered tracks). In region F, at the highest speed, lowest power combinations, no melting occurred.

Numerous researchers have investigated residual stresses and distortion in laser PBF processes using analytical and finite element methods. These studies have shown that residual stresses and subsequent part deflection increase with increase in track length. Based on these observations, dividing the scan area into small squares (Island scanning strategy) or stripes and then scanning each segment with short tracks are highly beneficial. Thus, there are multiple reasons for subdividing the layer cross-section into small regions for metals.

Randomization of square scanning (rather than scanning contiguous squares one after the other) and changing the primary scan direction between squares help alleviate preferential buildup of residual stresses, as shown in Fig. 5.8. In addition, scanning of stripes whereby the angle of the stripe changes each layer has a positive effect on the buildup of residual stress. As a result, stripes and square scan patterns are extensively utilized in PBF processes for metals.

When considering these results, it is clear that build speed optimization for metals is complex, as a simple maximization of scan speed for a particular power and scan spacing based on Eq. 5.1 are not possible. However, within process map regions A and B, Eq. 5.1 could still be used as a guide for process optimization.

Equation 5.1 solves for the energy density per surface area in $\left({}^{J}\!/_{m^2}\right)$. However, since the applied energy from a heat source is absorbed by a volume of the material, it is also helpful to calculate volumetric energy density $\left({}^{J}\!/_{m^3}\right)$. Equations 5.2 and 5.3

show simplified absorbed volumetric energy density ($\mathrm{ED_v}$) calculations for continuous and pulsed heat sources [16, 17].

$$\mathrm{ED_v} = \frac{P \times \eta_\mathrm{p}}{\mathrm{SS} \times \mathrm{HS} \times \mathrm{LT}} \tag{5.2}$$

$$\mathrm{ED_v} = \frac{P}{\frac{\mathrm{PD}}{\mathrm{ET}} \times \mathrm{HS} \times \mathrm{LT}} \tag{5.3}$$

where LT is layer thickness, η_p is powder absorptivity, PD is point distance (the distance traveled between spot centers during pulsed heating), and ET is exposure time per pulse. When we assume a melt pool is in the liquid phase until after a subsequent hatch, Eqs. 5.2 and 5.3 show the energy density. However, if the melt pool is solidified before the fusion of the next laser pass, Eq. 5.4 presents the absorbed volumetric energy density [17, 18].

$$\mathrm{ED_v} = \frac{P \times \eta_\mathrm{p}}{\mathrm{SS} \times \mathrm{BD} \times \mathrm{LT}} \tag{5.4}$$

where BD is beam diameter. In real conditions, to have a proper bonding between two subsequent layers, the melt pool depth must be more than the layer thickness. When calculating volumetric energy density as a function of melt pool depth (MD), Eq. 5.5 is used.

$$\mathrm{ED_v} = \frac{P \times \eta_\mathrm{p}}{\mathrm{SS} \times \mathrm{BD} \times \mathrm{MD}} \tag{5.5}$$

Melt pool depth is a function of heat penetration depth (δ_h) and is obtained according to Eq. 5.6. Melt pool depth typically ranges between 0.5 (δ_h) and 0.8 (δ_h) Heat penetration depth is a function of thermophysical properties of the material such as density (ρ), specific heat capacity (C_p), heat conductivity (K), and interaction time (t_i) of the heat source and material.

$$\delta_\mathrm{h} = 2\sqrt{\kappa t_\mathrm{i}} = 2\sqrt{\frac{K}{\rho C_\mathrm{p}} t_\mathrm{i}} \tag{5.6}$$

In the case of pulsed heat sources (such as a pulsed laser), t_i is pulse time. For a continuous heat source, $t_\mathrm{i} = \frac{\mathrm{BD}}{\mathrm{SS}}$. Generally, the input volumetric energy density is independent of the layer thickness and hatch spacing which is obtained according to Eq. 5.7 [19].

$$\mathrm{ED_v} = \frac{P}{\mathrm{SS} \times \mathrm{BD} \times \mathrm{MD}} \tag{5.7}$$

Equations 5.2, 5.3, 5.4, 5.5, 5.6 and 5.7 are simplified by neglecting heat of fusion, bed temperature/preheat condition, etc.

Another important phenomenon in PBF is heat dispersion. Most of the heat sources in PBF are monochromatic electromagnetic radiation beams, and the dispersion of the beam follows the Gaussian beam rules. Equation 5.8 shows the absorbed volumetric energy density by Gaussian dispersion ($\mathrm{ED_{vG}}$).

$$\mathrm{ED_{vG}} = \frac{2P \times \eta_{\mathrm{p}}}{\pi \times \mathrm{BD}^2 \times \mathrm{MD}} \exp\left(\frac{-2\left(\left(x - (\mathrm{SS} \times t)\right)^2 + y^2\right)}{\mathrm{BR}^2} \right) \tag{5.8}$$

where BR is beam radius. Equation 5.8 illustrates that the highest energy density is applied in the center of the beam [20, 21].

5.6 Powder Handling

5.6.1 Powder Handling Challenges

Several different systems for powder delivery in PBF processes have been developed. The lack of a single solution for powder delivery goes beyond simply avoiding patented embodiments of the counter-rotating roller. The development of other approaches has resulted in a broader range of powder types and morphologies which can be delivered.

Any powder delivery system for PBF must meet at least four characteristics:

- It must have a powder reservoir of sufficient volume to enable the process to build to the maximum build height without a need to pause the machine to refill the powder reservoir.
- The correct volume of powder must be transported from the powder reservoir to the build platform sufficient to cover the previous layer but without wasteful excess material.
- The powder must be spread to form a smooth, thin, repeatable layer thickness of powder.
- The powder spreading must not create excessive shear forces that disturb the previously processed layers.

In addition, any powder delivery system must be able to deal with these universal characteristics of powder feeding:

- As particle size decreases, interparticle friction and electrostatic forces increase. These result in a situation where powder can lose its flowability. (To illustrate this loss of flowability, compare the flow characteristics of a spoon full of granulated sugar to a spoon full of fine flour. The larger particle size sugar will flow out of the spoon at a relatively shallow angle, whereas the flour will stay in the spoon until the spoon is tipped at a large angle, at which point the flour will fall out as a large clump unless some perturbation (vibration, tapping, etc.) causes it to come out a small amount at a time.) Thus, any effective powder delivery system must make the powder flowable for effective delivery to occur.

- When the surface area to volume ratio of a particle increases, its surface energy increases and becomes more reactive. For certain materials, this means that the powder becomes explosive in the presence of oxygen; or it will burn if there is a spark. As a result, certain powders must be kept in an inert atmosphere while being processed, and powder handling should not result in the generation of sparks.
- When handled, small particles have a tendency to become airborne and float as a cloud of particles. In PBF machines, airborne particles will settle on surrounding surfaces, which may cloud optics, reduce the sensitivity of sensors, deflect laser beams, and damage moving parts. In addition, airborne particles have an effective surface area greater than packed powders, increasing their tendency to explode or burn. As a result, the powder delivery system should be designed in such a way that it minimizes the creation of airborne particles.
- Smaller powder particle sizes enable better surface finish, higher accuracy, and thinner layers. However, smaller powder particle sizes exacerbate all the problems just mentioned. As a result, each design for a powder delivery system is inherently a different approach to effectively feed the smallest possible powder particle sizes while minimizing the negative effects of these small powder particles.

5.6.2 Powder Handling Systems

The earliest commercialized LS powder delivery system, illustrated in Fig. 5.1, is one approach to optimizing these powder handling issues. The two feed cartridges represent the powder reservoir with sufficient material to completely fill the build platform to its greatest build height. The correct amount of powder for each layer is provided by accurately incrementing the feed cartridge up a prescribed amount and the build platform down by the layer thickness. The raised powder is then pushed by the counter-rotating roller over the build platform, depositing the powder. As long as the height of the roller remains constant, layers will be created at the thickness with which the build platform moves. The counter-rotating action of the roller creates a “wave” of powder flowing in front of the cylinder. The counterrotation pushes the powder up, fluidizing the powder being pushed, making it more flowable for a particular particle size and shape. The shear forces on the previously processed layers created by this counter-rotating roller are small, and thus the previously processed layers are relatively undisturbed.

Another commonly utilized solution for powder spreading is a doctor blade. A doctor blade is simply a thin piece of metal that is used to scrape material across the surface of a powder bed. When a doctor blade is used, the powder is not fluidized. Thus, the shear forces applied to the previously deposited layer are greater than for a counter-rotating roller. This increased shear can be reduced if the doctor blade is ultrasonically vibrated, thus partly fluidizing the powder being pushed.

An alternative approach to using a feed cartridge as a powder reservoir is to use a hopper feeding system. A hopper system delivers powder to the powder bed from above rather than beneath. The powder reservoir is typically separate from the build area, and a “feeding system” is used to fill the hopper. The hopper is then used to deposit powder in front of a roller or doctor blade, or a doctor blade or roller can be integrated with a hopper system for combined feeding and spreading. The feeding system (not shown) can have an additional reservoir that is external to the machine, so that powder can be added and then flooded with inert gas prior to being fed into the hopper. This type of powder handling system can also be combined with sieving, filtering, and other systems which enable automated powder recycling (see Sect. 5.5.3). For both feeding and spreading, ultrasonic vibration can be utilized with any of these approaches to help fluidize the powders. Two types of hopper-based powder delivery systems are illustrated in Fig. 5.11.

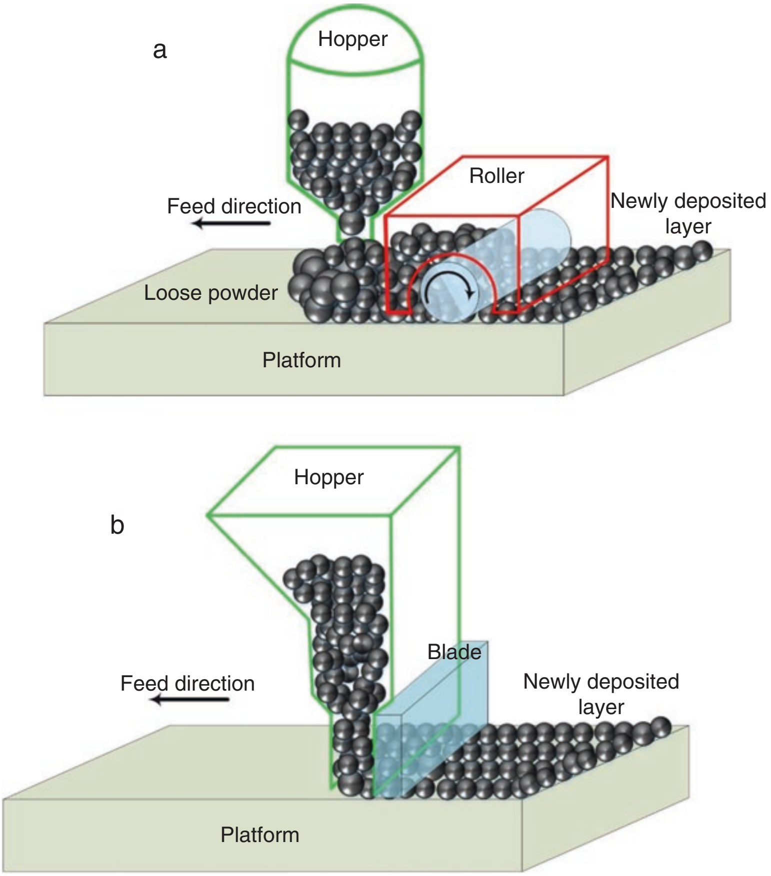


Fig. 5.11 Examples of hopper-based powder delivery systems [22]

In the case of multi-material powder bed processing, the only effective method is to use multiple hoppers with separate materials. In a multi-hopper system, the material type can be changed layer-by-layer. Although this has been demonstrated in a research environment and by some companies for very small parts, to date, all PBF technologies offered for sale commercially utilize a single-material powder feeding system.

5.6.3 Powder Recycling

As mentioned in Sect. 5.3.1, elevated-temperature sintering of the powder surrounding a part being built can cause the powder bed to fuse. In addition, elevated temperatures, particularly in the presence of reacting atmospheric gases, will also change the chemical nature of the powder particles. Similarly, holding polymer materials at elevated temperatures can change the molecular weight of the polymer. These combined effects mean that the properties of many different types of powders (particularly polymers) used in PBF processes change their properties when they are recycled and reused. For some materials these changes are small and thus are considered highly recyclable or infinitely recyclable. In other materials these changes are dramatic, and thus a highly controlled recycling methodology must be used to maintain consistent part properties between builds.

For the most popular PBF polymer material, nylon polyamide, both the effective particle size and molecular weight change during processing. As a result, a number of recycling methodologies have been developed to seek to maintain consistent build properties. The simplest approach to this recycling problem is to mix a specific ratio of unused powder with used powders. An example of a fraction-based mixture might be 1/3 unused powder, 1/3 overflow/feed powder, and 1/3 build platform powder. Overflow/feed and loose part-bed powder are handled separately, as they experience different temperature profiles during the build. The recaptured overflow/feed materials are only slightly modified from the original material as they have been subjected to lower temperatures only in the feed and overflow cartridges, whereas loose part-bed powder from the build platform has been maintained at an elevated temperature, sometimes for many hours.

Part-bed powder is typically processed using a particle sorting method, most commonly either a vibratory screen-based sifting device or an air classifier, before mixing with other powders. Air classifiers can be better than simple sifting, as they mix the powders together more effectively and help break up agglomerates, thus enabling a larger fraction of material to be recycled. However, air classifiers are more complex and expensive than sifting systems. Regardless of the particle sorting method used, it is critical that the material be well-mixed during recycling; otherwise, parts built from recycled powder will have different properties in different locations.

Although easy to implement, a simple fraction-based recycling approach will always result in some amount of mixing inconsistencies. This is due to the fact that different builds have different part layout characteristics, and thus the loose part-bed powder being recycled from one build has a different thermal history than loose part-bed powder being recycled from a different build.

In order to overcome some of the build-to-build inconsistencies inherent in fraction-based mixing, a recycling methodology based upon a powder's melt flow index (MFI) has been developed [23]. MFI is a measure of molten thermoplastic material flow through an extrusion apparatus under prescribed conditions. ASTM and ISO standards, for instance, can be followed to ensure repeatability. When using an MFI-based recycling methodology, a user determines a target MFI, based upon their experience. Used powders (part-bed and overflow/feed materials) are mixed and tested. Unused powder is also tested. The MFI for both is determined, and a well-blended mixture of unused and used powder is created and subsequently tested to achieve the target MFI. This may have to be done iteratively if the target MFI is not reached by the first mixture of unused to used powder. Using this methodology, the closer the target MFI is to the new powder MFI, the higher the new powder fraction and thus the more expensive the part. The MFI method is generally considered more effective for ensuring consistent build-to-build properties than fractional mixing.

Typically, most users find that they need less of the used build platform powder in their mixture than is produced. Thus, this excess build material becomes scrap. In addition, repeated recycling over a long period of time may result in some powder becoming unusable. As a result, the recyclability of a powder and the target MFI or fractional mixing selected by a user can have a significant effect on part properties and cost.

5.7 Powder Bed Fusion Process Variants and Commercial Machines

A large variety of PBF processes has been developed. To understand the practical differences between these processes, it is important to know how the powder delivery method, heating process, energy input type, atmospheric conditions, optics, and other features vary with respect to one another. An overview of commercial processes and a few notable systems under development are discussed in the following section.

5.7.1 Polymer Laser Sintering (pLS)

Prior to 2014 there were only two major producers of pLS machines, EOS and 3D Systems. The expiration of key patents in 2014 opened the door for many new companies to enter the marketplace. Polymer laser sintering machines are designed for directly processing polymers and for indirect processing of metals and ceramics.

Most commercial polymers were developed for processing via injection molding. The thermal and stress conditions for a material processed via pLS, however, are much different than the thermal and stress conditions for a material processed via injection molding. In injection molding the material is slowly heated under pressure, flows under high shear forces into a mold, and is cooled quickly. In pLS the material is heated very quickly as a laser beam passes, it flows via surface tension under gravitational forces, and it cools slowly over a period of hours to days. Since polymer microstructural features depend upon the time the material is held at elevated temperatures, polymer parts made using LS can have very different properties than polymer parts made using injection molding.

Many polymers which are easy to process using injection molding may not be processable using pLS. Figure 5.12 illustrates a schematic of a differential scanning calorimetry (DSC) curve for the types of melting characteristics which are desirable in a polymer for LS. In order to reduce residual stress-induced curling, pLS machines hold the powder bed temperature (T_{bed}) just below the temperature where melting begins ($T_{\text{Melt Onset}}$). When the laser melts a region of the powder bed, it should raise the temperature of the material above the melting temperature but below the temperature at which the material begins to deteriorate. If there is a small difference between the melting and deterioration temperatures, then the material will be difficult to successfully process in pLS.

After scanning, the molten cross-section will return over a relatively short period of time to the bed temperature (T_{Bed}). If the bed temperature is above the crystallization temperature of the material, then it will remain in a partially molten state for a very long time. This is advantageous for two reasons. First, by keeping the material partially molten, the part will not experience layer-by-layer accumulation of resid-

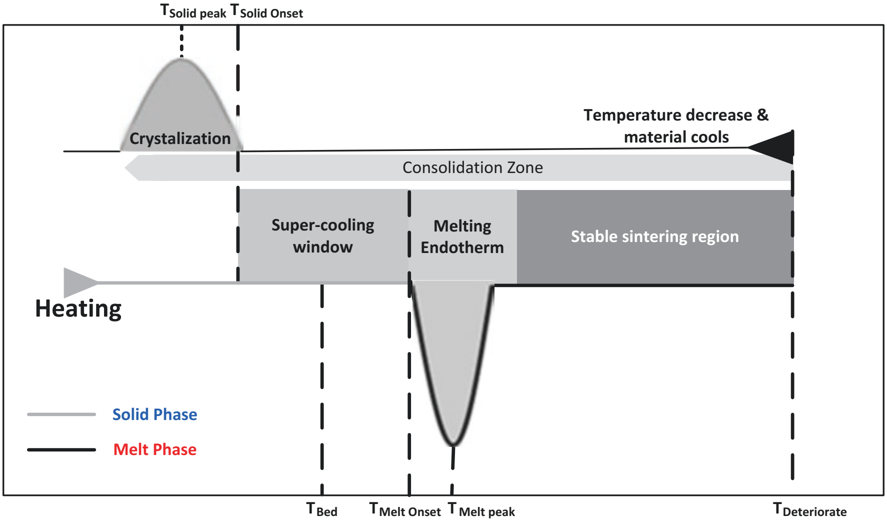


Fig. 5.12 Melting and solidification characteristics for an idealized polymer DSC curve for polymer laser sintering. (Photo courtesy of Neil Hopkinson, Sheffield University)

ual stresses and thus will be more accurate. Secondly, by holding the material in a semi-molten state for a long period of time, the part will achieve higher overall density. As a result, parts at the bottom of a build platform (which were built first and experience a longer time at elevated temperature) are denser than the last parts to be built. Thus, a key characteristic of a good polymer for pLS is that it has a broad “super-cooling window” as illustrated in Fig. 5.12. For most commercially available polymers, the melting curve overlaps the crystallization curve, and there is no super-cooling window. In addition, for amorphous polymers, there is no sharp onset of melting or crystallization. Thus pLS works best for polymers that are crystalline with a large super-cooling window and a high deterioration temperature.

The Selective Laser Sintering Sinterstation 2000 machine was the first commercial PBF system, introduced by the DTM Corporation, USA, in 1992. Subsequently, other variants were commercialized, and these systems are still manufactured and supplied by 3D Systems, USA, which purchased DTM in 2001. Newer machines offer several improvements over previous systems in terms of part accuracy, temperature uniformity, build speed, process repeatability, feature definition, and surface finish, but the basic processing features and system configuration remain unchanged from the description in Sect. 5.1. A typical pLS machine is limited to polymers with a melting temperature below 200 °C, whereas “high-temperature” pLS machines can process polymers with much higher melting temperature. Due to the use of CO_2 lasers and a nitrogen atmosphere with approximately 0.1–3.0% oxygen, pLS machines are incapable of directly processing pure metals or ceramics. Nylon polyamide materials are the most popular pLS materials, but these processes can also be used for many other types of polymer materials as well as indirect processing of metal and ceramic powders with polymer binders.

EOS GmbH, Germany, introduced its first EOSINT P machine in 1994 for producing plastic prototypes. In 1995, the company introduced its EOSINT M 250 machine for direct manufacture of metal casting molds from foundry sand. In 1998, the EOSINT M 250 Xtended machine was launched for direct metal laser sintering (DMLS), which was a liquid-phase sintering approach to processing metallic powders. These early metal machines used a special alloy mixture comprised of bronze and nickel powders developed by Electrolux Rapid Prototyping and licensed exclusively to EOS. The powder could be processed at low temperatures, required no preheating, and exhibited negligible shrinkage during processing; however, the end product was porous and was not representative of any common engineering metal alloys. Subsequently, EOS introduced many other materials and models, including platforms for foundry sand and full melting of metal powders (which will be discussed in the following section). One unique feature of EOS’s large-platform systems for polymers and foundry sand is the use of multiple laser beams for faster part construction (as illustrated in the 2 × 1D channels example in Fig. 2.6). This multi-machine approach to PBF has made EOS the market leader in this technology segment. A schematic of an EOS machine illustrating their approach to laser sintering powder delivery and processing for foundry sand is shown in Fig. 5.13.

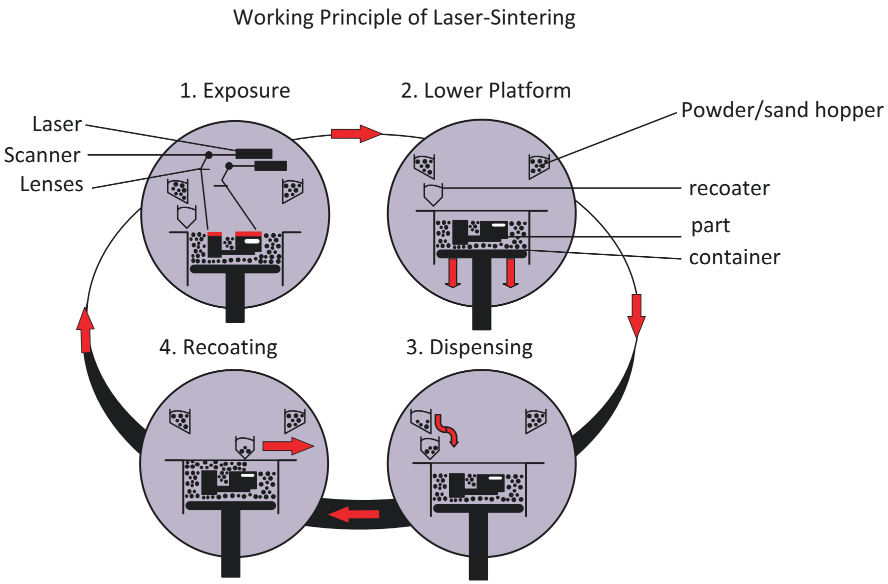


Fig. 5.13 Laser sintering schematic showing the dual-laser system option, hopper powder delivery, and a recoater that combines a movable hopper and doctor blade system

More recently, large-platform pLS systems commonly use a modular design. This modularity can include removable build platforms so that part cool-down and warm-up can occur outside of the chamber, enabling a fresh build platform to be inserted and used with minimal laser downtime; multiple build platform sizes; automated recycling and feeding of powder using a connected powder handling system; and better thermal control options.

In addition to commercial PBF machines, open-source polymer PBF machines are being developed to mimic the success of the RepRap effort for Material Extrusion (MEX) machines. In addition, inventors have applied PBF techniques to nonengineering applications via the CandyFab machine. Sugar is used as the powdered material, and a hot air nozzle is used as the energy source. By scanning the nozzle across the bed in a layer-by-layer fashion, sugar structures are made.

5.7.2 Laser-Based Systems for Metals and Ceramics

There are many companies which make commercially available laser-based systems for direct melting and sintering of metal powders: EOS (Germany), Renishaw (UK), Concept Laser (Germany), SLM Solutions (Germany), Realizer (Germany), 3D Systems (France/USA), Trumpf (Germany), Additive Industries (Netherlands), Velo3D (USA), Farsoon (China), and others are actively competing for market share. Although some of these companies have their own terminology for their machines, they are all laser PBF technologies. For simplicity, we will use metal laser sintering (mLS) to refer to the technologies in general and not to any particular variant.

mLS research in the late 1980s and early 1990s by various research groups was mostly unsuccessful. Compared to polymers, the high thermal conductivity, propensity to oxidize, high surface tension, and high laser reflectivity of metal powders make them significantly more difficult to process than polymers. Most commercially available mLS systems today are variants of the Selective Laser Powder Remelting (SLPR) approach developed by the Fraunhofer Institute for Laser Technology, Germany. Their research developed the basic processing techniques necessary for successful laser-based, point-wise melting of metals. The use of lasers with wavelengths better tuned to the absorptivity of metal powders was one key for enabling mLS. Fraunhofer used an Nd:YAG laser instead of the CO_2 laser used in pLS, which resulted in a much better absorptivity for metal powders (see Fig. 5.14). Subsequently, almost all mLS machines use fiber lasers, which in general are cheaper to purchase and maintain, more compact, and energy efficient and have better beam quality than Nd:YAG lasers. The other key enablers for mLS, compared to pLS, are different laser scan patterns (discussed previously), the use of f-theta lenses to minimize beam distortion during scanning, and low oxygen, inert atmosphere control.

One common practice among mLS manufacturers is the rigid attachment of their parts to a base plate at the bottom of the build platform. This is done to keep the metal part being built from distorting due to residual stresses. This means that the design flexibility for parts made from mLS is not as broad as the design flexibility for parts made using laser sintering of polymers, due to the need to remove these rigid supports using a machining or cutting operation.

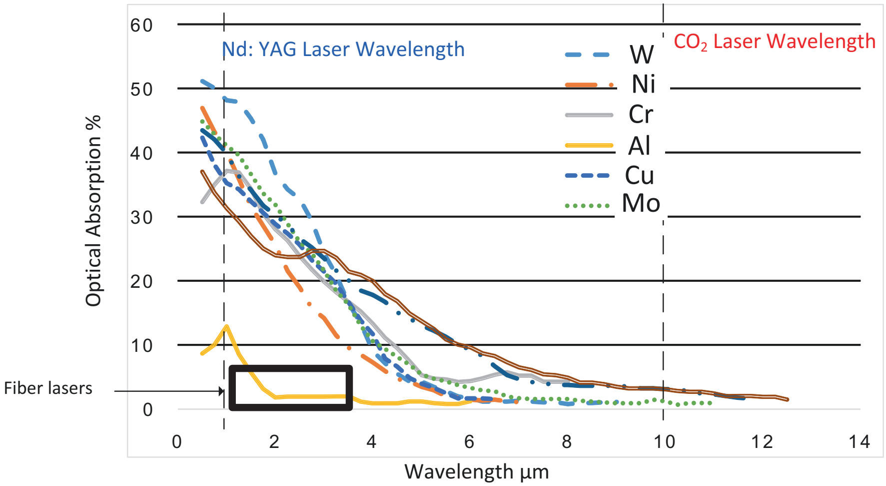


Fig. 5.14 Optical absorption % (absorptivity) of selected metals vs. wavelength (units are micrometers). (Courtesy of Optomec)

Fig. 5.15 3D-Micromac Powder Feed System. In this picture, only one of the powder feeders (located over the build cylinder) is filled with powder. (Photo courtesy of Laserinstitut Mittelsachsen e.V)

Over the years, various mLS machine manufacturers have sought to differentiate themselves from others by the features they offer. This differentiation includes laser power, number of lasers offered, powder handling systems, scanning strategies offered, maximum build volume, and more. Some machine manufacturers give users more control over the process parameters than other manufacturers, enabling more experimentation by the user, whereas other manufacturers only provide "proven" materials and process parameters. For instance, Renishaw machines have safety features to help minimize the risk of powder fires. EOS, as the world's most successful metal PBF provider, has spent considerable time tuning their machine process parameters and scanning strategies for specific materials which they sell to their customers.

3D-Micromac, Germany, produces a multi-material, small-scale mLS machine. It has developed small-scale mLS processes with small build cylinders (25–50 mm in diameter and 40 mm in height). Their fiber laser is focused to a particularly small spot size, for small feature definition. In order to use the fine powder particle sizes necessary for fine feature reproduction, they have developed a unique two-material powder feeding mechanism, shown in Fig. 5.15. The build platform is located between two powder feed cylinders. When the rotating rocker arm is above a powder feed cylinder, the powder is pushed up into the feeder, thus charging the hopper. When the rocker arm is moved over the top of the build platform, it deposits and smoothens the powder, moving away from the build cylinder prior to laser processing. By alternating between feed cylinders, the material being processed can be changed in a layer-by-layer fashion, thus forming multi-material structures. An example of a small impeller made using aluminum oxide powders is shown in Fig. 5.16.

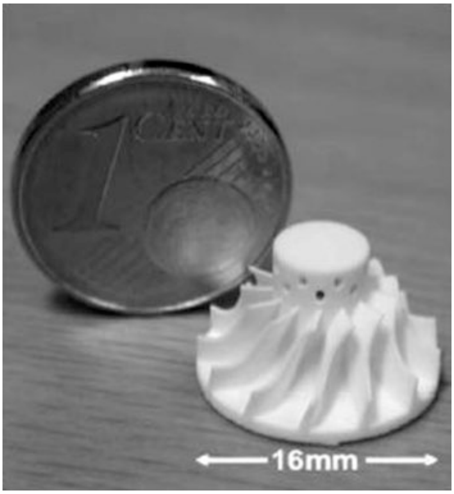


Fig. 5.16 Example 3D-Micromac part made from aluminum oxide powders. (Photo courtesy of Laserinstitut Mittelsachsen e.V)

5.7.3 Electron Beam Powder Bed Fusion

Electron Beam Powder Bed Fusion (EB-PBF) which is known as electron beam melting (EBM) by Arcam has become a successful approach to PBF. In contrast to laser-based systems, EB-PBF uses a high-energy electron beam to induce fusion between metal powder particles. This process was developed at Chalmers University of Technology, Sweden, and was commercialized by Arcam AB, Sweden in 2001, and now owned by GE.

Similarly to mLS, in the EB-PBF process, a focused electron beam scans across a thin layer of pre-laid powder, causing localized melting and resolidification per the slice cross-section. There are a number of differences between how mLS and EB-PBF are typically practiced, which are summarized in Table 5.2. Many of these differences are due to EB-PBF having an energy source of electrons, but other differences are due to engineering trade-offs as practiced in EB-PBF and mLS and are not necessarily inherent to the processing. A schematic illustration of an EB-PBF apparatus is shown as Fig. 5.17.

Laser beams heat the powder when photons are absorbed by powder particles. Electron beams, however, heat powder by transfer of kinetic energy from incoming electrons into powder particles. As powder particles absorb electrons, they gain an increasingly negative charge. This has two potentially detrimental effects: (1) if the repulsive force of neighboring negatively charged particles overcomes the gravitational and frictional forces holding them in place, there will be a rapid expulsion of powder particles from the powder bed, creating a powder cloud (which is worse for fine powders than coarser powders); and (2) increasing negative charges in the powder particles will tend to repel the incoming negatively charged electrons, thus creating a more diffuse beam. There are no such complimentary phenomena with photons. As a result, the conductivity of the powder bed in EB-PBF must be high enough that powder particles do not become highly negatively charged, and scan

Table 5.2 Differences between EB-PBF and MLS

Characteristic	Electron beam melting	Metal laser sintering
Thermal source	Electron beam	Laser
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Galvanometers
Energy absorption	Conductivity-limited	Absorptivity-limited
Powder preheating	Use electron beam	Use infrared or resistive heaters
Scan speeds	Very fast, magnetically driven	Limited by galvanometer inertia
Energy costs	Moderate	High
Surface finish	Moderate to poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals, and ceramics
Powder particle size	Medium	Fine

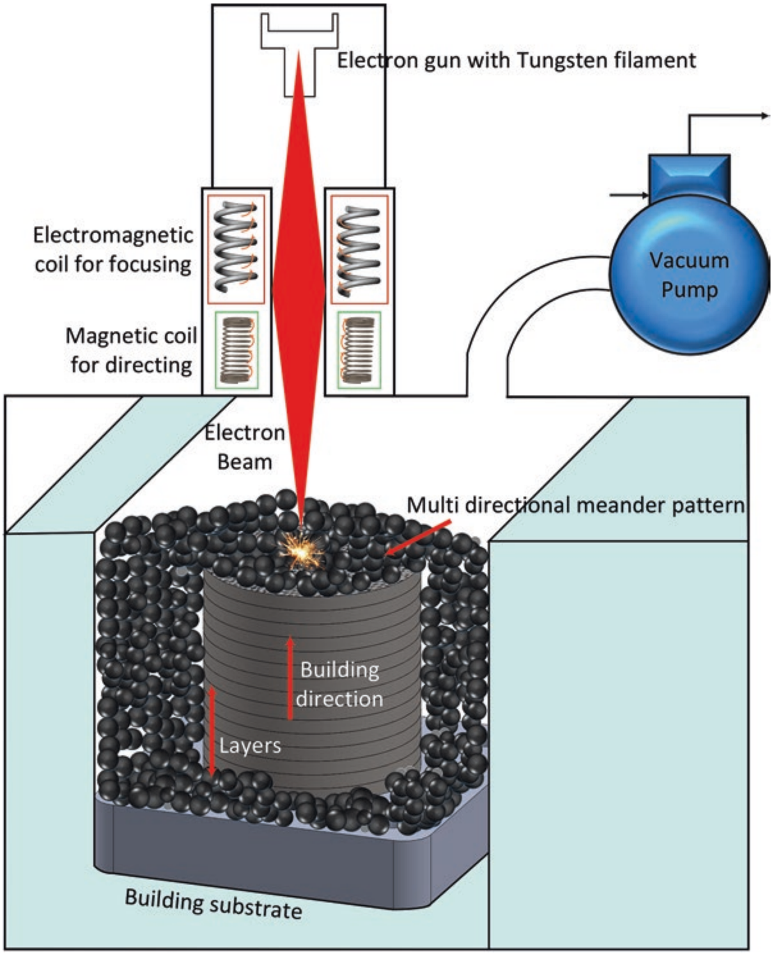


Fig. 5.17 Schematic of an EB-PBF apparatus

strategies must be used to avoid buildup of regions of negatively charged particles. In practice, electron beam energy is more diffuse, in part, so as not to build up too great a negative charge in any one location. As a result, the effective melt pool size increases, creating a larger heat-affected zone. Consequently, the minimum feature size, median powder particle size, layer thickness, resolution, and surface finish of an EB-PBF process are typically larger than for an mLS process.

As mentioned above, in EB-PBF the powder bed must be conductive. Thus, EB-PBF can only be used to process conductive materials (e.g., metals), whereas lasers can be used with any material that absorbs energy at the laser wavelength (e.g., metals, polymers, and ceramics).

Electron beam generation is typically a much more efficient process than laser beam generation. When a voltage difference is applied to the heated filament in an electron beam system, most of the electrical energy is converted into the electron beam; and higher beam energies (above 1 kW) are available at a moderate cost. In contrast, it is common for only 10–20% of the total electrical energy input for laser systems to be converted into beam energy, with the remaining energy lost in the form of heat. In addition, lasers with beam energies above 1 kW are typically much more expensive than comparable electron beams with similar energies. Thus, electron beams are a less costly high-energy source than laser beams. Newer fiber lasers, however, are more simple in their design, more reliable to maintain, and more efficient to use (with conversion efficiencies reported of 70–80% for some fiber lasers). Thus, this energy advantage for electron beams may not be a major advantage in the future.

EB-PBF powder beds are maintained at a higher temperature than mLS powder beds. There are several reasons for this. First, the higher energy input of the beam used in the EB-PBF system naturally heats the surrounding loose powder to a higher temperature than the lower-energy laser beams. In order to maintain a steady-state uniform temperature throughout the build (rather than having the build become hotter as the build height increases), the EB-PBF process uses the electron beam to heat the metal substrate at the bottom of the build platform before laying a powder bed. By defocusing the electron beam and scanning it very rapidly over the entire surface of the substrate (or the powder bed for subsequently layers), the bed can be preheated rapidly and uniformly to any pre-set temperature. As a result, the radiative and resistive heaters present in some mLS systems for substrate and powder bed heating are not used in EB-PBF. By maintaining the powder bed at an elevated temperature, however, the resulting microstructure of a typical EB-PBF part is significantly different from a typical mLS part (see Fig. 5.18). In particular, in mLS the individual laser scan lines are typically easily distinguishable, whereas individual scan lines are often indistinguishable in EB-PBF microstructures. Rapid cooling in mLS creates smaller grain sizes, and subsequent layer scans only partially remelt the previously deposited layer. The powder bed is held at a low enough temperature that elevated-temperature grain growth does not erase the layering effects. In EB-PBF, the higher temperature of the powder bed, and the larger and more diffuse heat input results in a contiguous grain pattern that is more representative of a cast microstructure, with less porosity than an mLS microstructure.

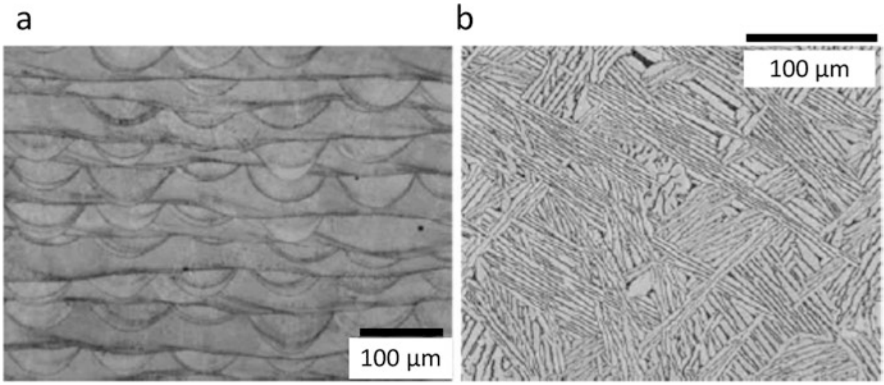


Fig. 5.18 Representative CoCrMo mLS microstructure ((**a**) photo courtesy of EOS) and Ti6Al4V EB-PBF microstructure ((**b**), photo courtesy of Arcam)

Although the microstructures presented in Fig. 5.18 are representative of mLS and EB-PBF, it should be noted that the presence of beam traces in the final microstructure (as seen in the left image of Fig. 5.18) is process parameter and material dependent. For certain alloys, such as titanium, it is not uncommon for contiguous grain growth across layers even for mLS. For other materials, such as those that have a higher melting point, the layering may be more prevalent. In addition, layering is more prevalent for process parameter combinations of lower bed temperature, lower beam energy, faster scan rate, thicker layers, and/or larger scan spacing for both mLS and EB-PBF. The reader is also referred to the presentation of material microstructures and process parameter effects of the DED processes in Sects. 10.6 and 10.7, since the phenomena seen in mLS and EB-PBF are similar to those observed in DED processes.

One of the most promising aspects of EB-PBF is the ability to move the beam nearly instantaneously. The current control system for EB-PBF machines makes use of this capability to keep multiple melt pools moving simultaneously for part contour scanning. Future improvements to scanning strategies may dramatically increase the build speed of EB-PBF over mLS, helping to distinguish it even more for certain applications. For instance, when nonsolid cross-sections are created, in particular when scanning truss-like structures (with designed internal porosity), nearly instantaneous beam motion from one scan location to another can dramatically speed up the production of the overall product.

In EB-PBF, residual stresses are much lower than for mLS due to the elevated bed temperature. Supports are needed to provide electrical conduction through the powder bed to the base plate, to eliminate electron charging, but the mass of these supports is an order of magnitude less than what is needed for mLS of a similar geometry. Future scan strategies for mLS may help reduce the need for supports to a degree where they can be removed easily, but at present EB-PBF has a clear advantage when it comes to minimizing residual stress and supports.

5.7.4 Line-Wise and Layer-Wise PBF Processes for Polymers

PBF processes have proven to be the most flexible general approach to AM. For production of end-use components, PBF processes surpass the applicability of any other approach. However, the use of expensive lasers in most processes, the fact that these lasers can only process one "point" of material at any instant in time, and the overall cost of the systems mean that there is considerable room for improvement. High-speed sintering, described above, and other variants of PBF are being researched and commercialized to fuse lines or layers of polymer material at a time. To date no commercial systems for metal line-wise or layer-wise processes have been introduced, but this is also an area of research interest. Polymer PBF processing in a line-wise or layer-wise manner dramatically increases the build rate of PBF processes, thus making them more cost-competitive. Three general approaches are discussed below. All three utilize infrared energy to induce fusion in powder beds; the key differences lay in their approach to controlling which portions of the powder bed fuse and which remain unfused, as illustrated in Fig. 5.19.

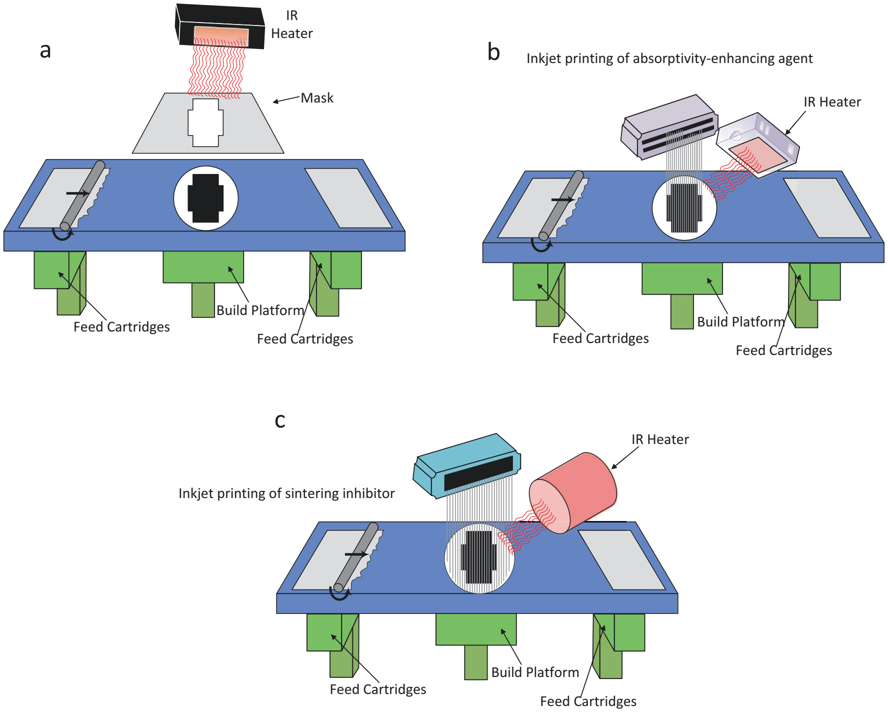


Fig. 5.19 Three different approaches to line- and layer-wise PBF processing (**a**) mask-based sintering, (**b**) printing of an absorptivity-enhancing agent in the part region, and (**c**) printing of a sintering inhibitor outside the part region

Sintermask GmbH, Germany, founded in 2009, sold several Selective Mask Sintering (SMS) machines, based upon technology developed at Speedparts AB before going out of business. The key characteristics of their technology were exposure of an entire layer at a time to infrared thermal energy through a mask and rapid layering of powdered material. Their powder delivery system deposited a new layer of powder in 3 s. Heat energy was provided by an infrared heater. A dynamic mask system, similar to those used in a photocopier to transfer ink to paper, was used between the heater and the powder bed. This was a rebirth of an idea commercialized by Cubital for layer-wise photopolymerization in the early days of AM, as mentioned in Chap. 2. The SMS mask allows infrared energy to impinge on the powder bed only in the region prescribed by the layer cross-section, fusing powder in approximately 1 s [24, 25]. From a materials standpoint, the use of an infrared energy source means that the powder must readily absorb and quickly sinter or melt in the presence of infrared energy. Most materials with this characteristic are dark colored (e.g., gray or black), and thus color choice limitations may be a factor for some adopters of the technology. It appears that development of this technology is on hold, as of the writing of this book [26].

High-speed sintering was developed at Loughborough University and Sheffield University. As mentioned above, in HSS an inkjet printer is used to deposit ink onto the powder bed, representing a part's cross-section for that layer. Inks are especially formulated to significantly enhance infrared absorption compared with the surrounding powder bed. An infrared heater is used to scan the entire powder bed quickly, following inkjetting. Thus, this process is an example of line-wise processing. The difference between the absorptivity of the unprinted areas compared to the printed areas means that the unprinted areas do not absorb enough energy to sinter, whereas the powder in the printed areas sinters and/or melts. As the distinguishing factor between the fused and unfused region is the enhanced absorption of energy where printing occurs, the inks are often gray or black and thus affect the color of the final part.

A third approach to rapid PBF is the selective inhibition sintering (SIS) process, developed at the University of Southern California. In contrast to HSS, a sintering inhibitor is printed in regions where fusion is not desired, followed by exposure to infrared radiation. In this case, the inhibitor interferes with diffusion and surface properties to inhibit sintering. In addition, researchers have also utilized movable plates to mask portions of the powder bed where no sintering is desired, in order to minimize the amount of inhibitor required. One benefit of SIS over the previous two is that it does not involve adding an infrared absorption agent into the part itself, and thus the untreated powder becomes the material in the part. However, the unused powder in the powder bed is not easily recyclable, as it has been "contaminated" with inhibitor, and thus, there is significant unrecyclable material created.

Two additional variations of inkjet printing combined with PBF methodology are also practiced in SIS and by fcubic AB. In SIS, if no sintering is performed during the build (i.e., inhibitor is printed but no thermal infrared energy is scanned), the entire part bed can be moved into an oven where the powder is sintered to achieve fusion within the part, but not in areas where inhibitor has been printed.

fcubic AB, Sweden, uses inkjet printing plus sintering in a furnace to compete with traditional powder metallurgy for stainless steel components. A sintering aid is printed in the regions representing the part cross-section, so that this region will fuse more rapidly in a furnace. A sintering aid is an element or alloy which increases the rate at which solid-state sintering occurs between particles by changing surface characteristics and/or by reacting with the particles. Thus, sintering in the part will occur at lower temperatures and times than for the surrounding powder that has not received a sintering aid.

Both SIS and fcubic are similar to the BJT processes described in Chap. 8 (such as practiced by ExOne and Voxeljet) where a binder joins powders in regions of the powder bed where the part is located followed by furnace processing. There is, however, one key aspect of SIS and the fcubic processing which is different than these approaches. In the SIS and fcubic processes, the printed material is a sintering aid or inhibitor rather than a binder, and the part *remains embedded* within the powder bed when sintering in the furnace. Using the ExOne process, for instance, the machine prints a binder to glue powder particles together; and the bound regions are *removed from the powder bed* as a green part before sintering in a furnace (much like the indirect metal processing discussed earlier).

Common to all of the line-wise and layer-wise PBF processes is the need to differentiate between fusion in the part and the remaining powder. Too low total energy input will leave the part weak and only partially sintered. Too high energy levels will result in part growth by sintering of excess surrounding powder to the part and/or degradation of the surrounding powder to the point where it cannot be easily recycled. Most importantly, in all cases, it is the *difference* between fusion induced in the part and fusion induced in the surrounding powder bed that is the key factor to control.

5.8 Process Benefits and Drawbacks

Due to its nature, PBF can process a very wide variety of materials, in contrast to many other AM processes. Although it is easier to control the processing of semicrystalline polymers, the PBF processing of amorphous polymers has been successful. Many metals can be processed; as mentioned, if a metal can be welded, it is a good candidate for mLS. Few ceramic materials are commercially available, but quite a few others have been demonstrated in research.

During part building, loose powder is a sufficient support material for polymer PBF. This saves significant time during part building and post-processing and enables advanced geometries that are difficult to post-process when supports are necessary. As a result, internal cooling channels and other complex features that would be impossible to machine are possible in polymer PBF.

Supports, however, are required for most metal PBF processes. The high residual stresses experienced when processing metals mean that support structures are typically required to keep the part from excessive warping. This means that post-processing of metal parts after AM can be expensive and time-consuming. Small features (including internal cooling channels) can usually be formed without supports; but the part itself is usually constrained to a substrate at the bottom of the build platform to keep it from warping. As a result, the orientation of the part and the location of supports are key factors when setting up a build.

Accuracy and surface finish of powder-based AM processes are typically inferior to liquid-based processes. However, accuracy and surface finish are strongly influenced by the operating conditions and the powder particle size. Finer particle sizes produce smoother, more accurate parts but are difficult to spread and handle. Larger particle sizes facilitate easier powder processing and delivery but hurt surface finish, minimum feature size, and minimum layer thickness. The build materials used in these processes typically exhibit 3–4% shrinkage, which can lead to part distortion. Materials with low thermal conductivity result in better accuracy as melt pool and solidification are more controllable and part growth is minimized when heat conduction is minimized.

With PBF processes, total part construction time can take longer than other Additive Manufacturing processes because of the preheat and cool-down cycles involved. However, as is the case with several newer machine designs, removable build platforms enable preheat and cool-down to occur off-line, thus enabling much greater machine productivity. Additionally, the ability to nest polymer parts in three dimensions, as no support structures are needed, means that many parts can be produced in a single build, thus dramatically improving the productivity of these processes when compared with processes that require supports. Figure 5.20 shows examples of polymer and metal parts made using PBF.

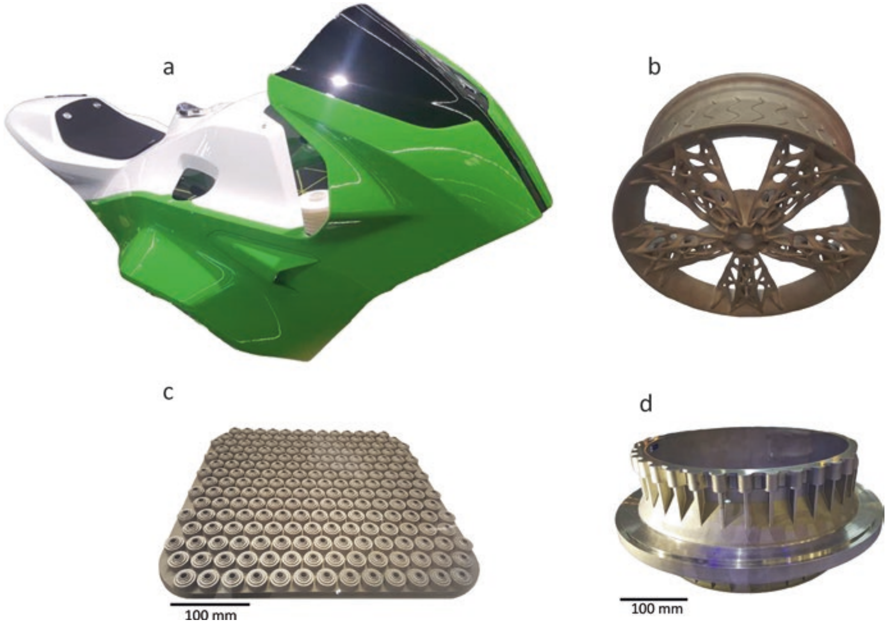


Fig. 5.20 (**a**) Motorcycle frame from FKM Laser Sintering, (**b**) wheel rims from BLT, (**c**) series of prototypes from Additive Industries, and (**d**) Vulcan rocket propellant nozzles from GE

5.9 Summary

PBF processes were one of the earliest AM processes and continue to be one of the most popular. Polymer-based laser sintering is commonly used for prototyping and end-use applications in many industries, competing with injection molding and other polymer manufacturing processes. PBF processes are particularly competitive for low-to-medium volume geometrically complex parts.

Metal-based processes, including laser and electron beam, are one of the fastest growing areas of AM around the world. Metal PBF processes are becoming increasingly common for aerospace and biomedical applications, due to their inherent geometric complexity benefits and their excellent material properties.

As methods for moving from point-wise to line-wise to layer-wise PBF are improved and commercialized, build times and cost will decrease. This will make PBF processing even more competitive. The future for PBF remains bright; and it is likely that PBF processes will remain one of the most common types of AM technologies for the foreseeable future.

5.10 Questions

1. Find a reference which describes an application of the Arrhenius equation to solid-state sintering. If an acceptable level of sintering is achieved within time T_1 at a temperature of 750 K, what temperature would be required to achieve the same level of sintering in half the time?
2. Estimate the energy driving force difference between two different powder beds made up of spherical particles with the same total mass, where the difference in surface area to volume ratio difference between one powder bed and the other is a factor of 2.
3. Explain the pros and cons of the various binder and structural material alternatives in liquid-phase sintering (Sect. 5.3.3.1) for a bone tissue scaffold application, where the binder (matrix material) is PCL and the structural material is hydroxyapatite.
4. Using standard kitchen ingredients, explore the powder characteristics described in Sect. 5.5.1 and powder handling options described in Sect. 5.5.2. Using at least three different ingredients, describe whether or not the issues described are reproducible in your experiments.
5. Using an internet search, find a set of recommended processing parameters for nylon polyamide using laser sintering. Based upon Eq. (5.1), are these parameters limited by machine laser power, scan spacing, or scan speed? Why? What machine characteristics could be changed to increase the build rate for this material and machine combination?
6. Using Fig. 5.10 and the explanatory text, estimate the minimum laser dwell time (how long a spot is under the laser as it passes) needed to maintain a type B scan track at 100 W.

7. What are some of the differences between fiber lasers and Nd:YAG lasers?
8. Why is electron beam generation typically a much more energy efficient process than laser beam generation?
9. What are the inherent differences between Laser-Based Powder Bed Fusion (LB-PBF) and Electron Beam Powder Bed Fusion (EB-PBF)?
10. What are the benefits of using the powder in polymer PBF as supporting material?
11. Consider the use of different materials, spreading techniques, and material thicknesses. What are the primary factors to be considered for a powder delivery system in a Powder Bed Fusion process? What are the benefits associated with using a counter-rotating roller compared to a doctor blade when it comes to distributing new layers of powder?
12. Discuss how Selective Laser Sintering keeps parts from curling, for both polymer and metal parts. How do these processes reduce the amount of curling?
13. How does the orientation of the part inside an SLS machine affect the final part?
14. Which Powder Bed Fusion process can be used on the macro- and microscale and describe their differences?
15. How are different powders handled in the case of multi-material powder bed processing?
16. What is Melt Flow Index (MFI)? How is it used in powder recycling in the Powder Bed Fusion process?
17. Why should the powder bed be conductive in EB-PBF?
18. Why are thermoplastic materials well-suited for Powder Bed Fusion process?
19. What are the most common lasers in Additive Manufacturing? Compare these lasers, and give the specific uses in AM where each type of laser has an advantage.
20. What is the balling effect in PBF? How is it avoided?
21. A set of experiment using a LB-PBF machine with M2 tool steel (1C-4.15Cr-6.4W-5Mo-2V-bal.Fe) tool steel is shown in Table Q5.1. Determine the energy density values for the single layer experiments. What is the optimal energy

Table Q5.1 Question 21

Experiment	Laser power (W)	Scan speed (mm/s)	Scan spacing (% of beam width)	Layer thickness (mm)
Single tracks	32, 58, 77, 110, 143, 170	0.5, 1–12	N/A	N/A
Single layer	58, 77, 110, 143	0.5, 1, 3, 5, 8, 10	25, 50, 100	N/A
Multiple layers	143	5, 8, 10	25, 50	0.4
Two beam widths of 0.55 and 1.1 mm were used				

required to fully melt this material? Why do you suppose they performed these experiments at the prescribed energy densities?

22. The polymers used in Selective Laser Sintering are semi-crystalline polymers which exhibit glass transition temperature (T_g). In this case, part bed temperature should be set close to T_g
    The glass transition temperature of polyethylene terephthalate (PET) and poly vinyl alcohol (PVA) are 70° and 85°, respectively. Assume that the T_g of a mixture is proportional to the volume ratio of the two constituent materials.
    Note: W_1 and W_2 are the volume fraction of two materials. $\frac{1}{T_g} = \frac{W1}{T_{g1}} + \frac{W2}{T_{g2}}$
    (a) Calculate the glass temperature when the volume ration of PET is 10%, 20%, 30%, 40%, and 50%.
    (b) Plot T_g as a function of T_{g1} and W_1.
23. Use the formula provided in the text book for the solidification rate, and explain how changing the scanning rate would affect the cooling rate and consequently grain size. Use the figures provided in the text book for justification of your answer.

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