

UNIT-4

POWDER BED FUSION AND MATERIAL EXTRUSION

4.1 Selective Laser Sintering (SLS)

Powder bed fusion (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. 4.1, and all other PBF processes modify this basic approach in one or more ways to enhance machine productivity, enable different materials to be processed, and/or to avoid specific patented features.

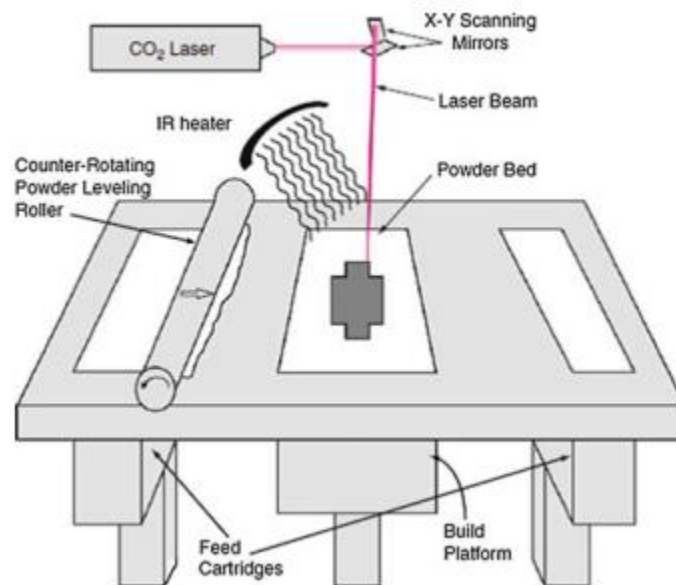
All PBF processes share a basic set of characteristics. These include one or more thermal sources for inducing fusion between powder particles, a method for controlling powder fusion to a prescribed region of each layer, and mechanisms for adding and smoothing powder layers. The most common thermal sources 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, as 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.

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 are being 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.

In order to provide a baseline description of powder fusion processes, pLS will be described as the paradigm approach to which the other PBF processes will be compared. As shown in Fig. 4.1, 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 is 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 nonuniform thermal expansion and contraction (resulting in curling).

Once an appropriate powder layer has been formed and preheated, a focused CO₂ 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 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 Fig. 4.1 Schematic of the selective laser sintering process 108 5 Powder Bed Fusion Processes 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/or powder bed are prematurely exposed to ambient temperature and atmosphere, the powders may degrade in the presence of oxygen and 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.



4.1 Schematic of the selective laser sintering process

4.2 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.

4.2.1 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, but this is uncommon. Much more common are semi-crystalline polymers which have regions of regular structure, called crystallites. 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 US 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 quickly, forming part of a cross section. In contrast, amorphous polymers tend to soften and melt over a broad temperature range 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 approach 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-Llactide (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.

4.2.2 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-base alloys, some aluminum alloys, and cobalt-chrome have been processed and are commercially available in some form. Additionally, some companies now 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. Parts produced using RapidSteel were debinded (350–450 C), sintered (around 1,000 C), and finally infiltrated with Cu (1,120 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. Subsequently, 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 nickel-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 melting (EBM) 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 EBM processes advance, the types of metal alloys which are commonly utilized will grow and new alloys specifically tailored for PBF production will be developed.

4.2.3 Ceramics and Ceramic Composites

Ceramic materials are generally described as compounds that consist of metaloxides, carbides, and 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. 3D Systems also says it offers cermets, which are metal-ceramic composites.

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.

4.3 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. However, the use of a single word to describe the powder fusion mechanism is inherently problematic as multiple mechanisms are possible. There are four different fusion mechanisms which are present in PBF processes [1]. These include solid-state sintering, chemically induced binding, liquid-phase sintering (LPS), and full melting. Most commercial processes utilize primarily LPS and melting. A brief description of each of these mechanisms and their relevance to AM follows.

4.3.1 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

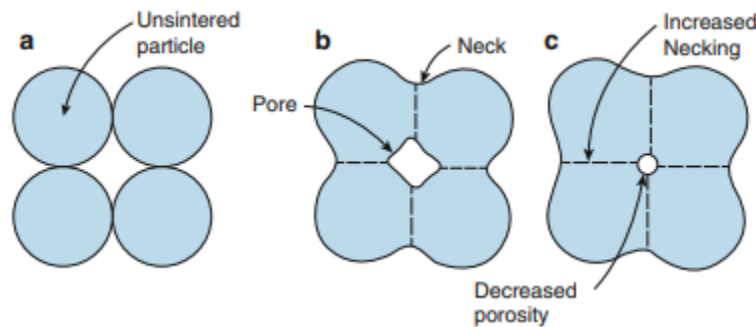


Fig. 4.2 Solid-state sintering. (a) Closely packed particles prior to sintering. (b) Particles agglomerate at temperatures above one half of the absolute melting temperature, as they seek to minimize free energy by decreasing surface area. (c) As sintering progresses, neck size increases and pore size decrease

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 SA , through the equation $E_s \propto \gamma_s SA$ (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.

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.

1. 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.

2. As a part is being formed in the build platform, thermally induced fusing 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) 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. 4.3 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, 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.

3. 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 part bed temperature, cooling rate and other parameters. EBM, in particular, often makes use of the positive aspects of elevated-temperature solidstate 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.

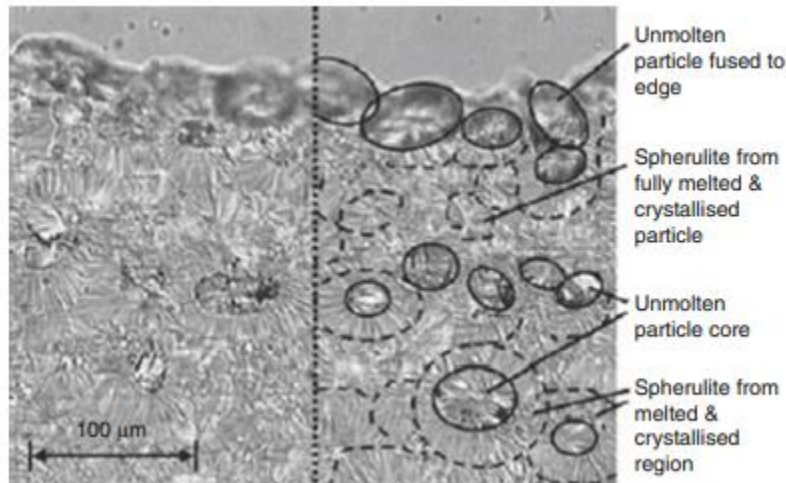


Fig. 4.3 Typical pLS microstructure for nylon polyamide (Materials Science & Engineering. A. Structural Materials: Properties, Microstructure and Processing by Zarringhalam, H., Hopkinson, N., Kamperman, N.F., de Vlieger, J.J. Copyright 2006 by Elsevier Science & Technology Journals. Reproduced with permission of Elsevier Science & Technology Journals in the format Textbook via Copyright Clearance Center) [5]

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 SiO₂ forms and binds together a composite of SiC and SiO₂; laser processing of ZrB₂ in the presence of oxygen, whereby ZrO₂

forms and binds together a composite of ZrB₂ and ZrO₂; and laser processing of Al in the presence of N₂, 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 pre-mixed 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 postprocessing have limited the adoption of chemically induced sintering in commercial machines.

4.3.3 LPS and Partial Melting

LPS is arguably the most versatile mechanism for PBF. LPS 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 become 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-meltingpoint constituent to glue together particles of WC.

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. [1] has formed the basis for the distinctions discussed in the following section and shown in Fig. 5.4

4.3.3.1 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 postprocessing (e.g., to lower or fill the porosity) are termed as “green” parts.

In some cases, the density of the binder and structural material are 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

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.

Coated Particles

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.

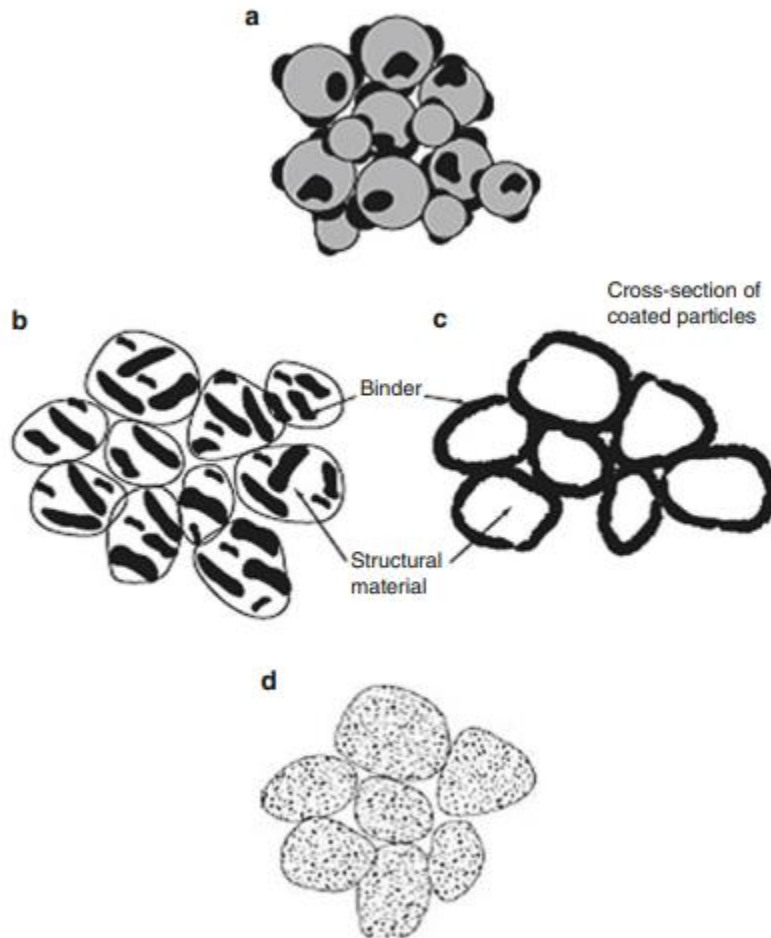


Fig. 4.4 Liquid phase sintering variations used in powder bed fusion processing: (a) separate particles, (b) composite particles, (c) coated particles, and (d) indistinct mixtures. Darker regions represent the lower-melting-temperature binder material. Lighter regions represent the highmelting-temperature structural material. For indistinct mixtures, microstructural alloying eliminates distinct binder and structural regions

4.3.3.2 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. 4.3). 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 noneutectic 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 (DMLS) machines. Subsequent mLS commercialized processes are all designed to fully melt the metal alloys they process.

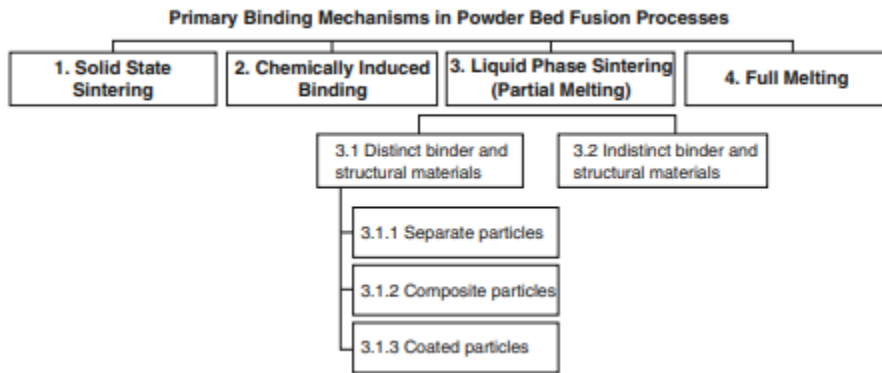
4.3.4 Full Melting

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 re-melt 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. 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

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 results in unique properties that are distinct from, and can sometime be more desirable than, cast or wrought parts made from identical alloys.

Figure 4.5 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,” “Laser Cusing,” “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.



4.4 Laser-Based Systems for Metals and Ceramics

Selective Laser Melting (SLM)

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), Selective Laser Melting (SLM) Solutions (Germany), Realizer (Germany), and 3D Systems (France/USA). There are competing terminologies for these technologies. The term selective laser melting (SLM) is used by numerous companies; however the terms Laser Cusing and DMLS are also used by certain manufacturers. For this discussion, we will use 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 re-melting (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 CO₂ laser used in pLS, which resulted in a much better absorptivity for metal powders (see Fig. 5.13). Subsequently, almost all mLS machines use fiber lasers, which in general are cheaper to purchase and maintain, more compact, 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 in the following section), 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 quite 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

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. Concept Laser has focused on the development of stainless and hot-work steel alloys suitable for injection mold and die cast tooling. 3D Systems (after their acquisition of Phenix Systems) has developed machines which can be held at an elevated temperature, thus enabling efficient sintering of ceramic powders, in addition to melting of metal powders. Another unique characteristic of the 3D Systems machine is its use of a roller to spread and then compact powder, making it the only manufacturer which can directly change the powder bed packing density on-the-fly.

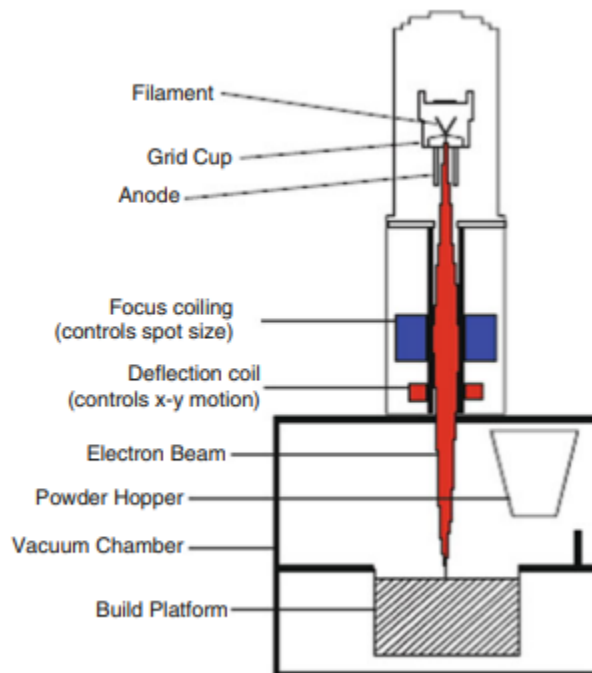
3D-Micromac, Germany, a partner of EOS, produces the only multimaterial, small-scale mLS machine. It has developed small-scale mLS processes with small build cylinders 25 or 50 mm in diameter and 40 mm in height. Their fiber laser is focused to a particularly small spot size, for small feature definition. 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. 5.14. 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 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 multimaterial structures. An example of a small impeller made using aluminum oxide powders is shown in Fig. 4.5.



Fig 4.5 3D Micromac Powder Feed System. In this picture, only one of the powder feeders (located over the build cylinder) is filled with powder (courtesy: Laserinstitut Mittelsachsen e.V.

4.5 Electron Beam Melting

Fig. 5.16 Schematic of an EBM apparatus (courtesy: Arcam)



Electron beam melting (EBM) has become a successful approach to PBF. In contrast to laser-based systems, EBM 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.

Similarly to mLS, in the EBM 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 EBM are typically practiced, which are summarized in Table 5.1. Many of these differences are due to EBM having an energy source of

electrons, but other differences are due to engineering trade-offs as practiced in EBM and mLS and are not necessarily inherent to the processing. A schematic illustration of an EBM apparatus is shown in Fig. 5.16.

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 EBM must be high enough that powder particles do not become highly negatively charged, and scan strategies must be used to avoid build-up 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 EBM process are typically larger than for an mLS process.

As mentioned above, in EBM the powder bed must be conductive. Thus, EBM 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.

EBM 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 EBM 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 EBM 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 preset temperature. As a result, the radiative and resistive heaters present in some mLS systems for substrate and powder bed heating are not used in EBM. By maintaining the powder bed at an elevated temperature, however, the resulting microstructure of a typical EBM part is significantly different from a typical mLS part (see Fig. 5.17). In particular, in mLS the individual laser scan lines are typically easily distinguishable, whereas individual scan lines are often indistinguishable in EBM microstructures. Rapid cooling in mLS creates smaller grain sizes and subsequent layer scans only partially re-melt 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 EBM, the higher temperature of the powder bed, and the larger and more diffuse heat input result in a contiguous grain pattern that is more representative of a cast microstructure, with less porosity than an mLS microstructure.

Although the microstructures presented in Fig. 5.17 are representative of mLS and EBM, it should be noted that the presence of beam traces in the final microstructure (as seen in the left image of Fig. 5.17) 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 EBM. 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 EBM are similar to those observed in DED processes.

One of the most promising aspects of EBM is the ability to move the beam nearly instantaneously. The current control system for EBM 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 EBM 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 EBM, 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 EBM has a clear advantage when it comes to minimizing residual stress and supports.

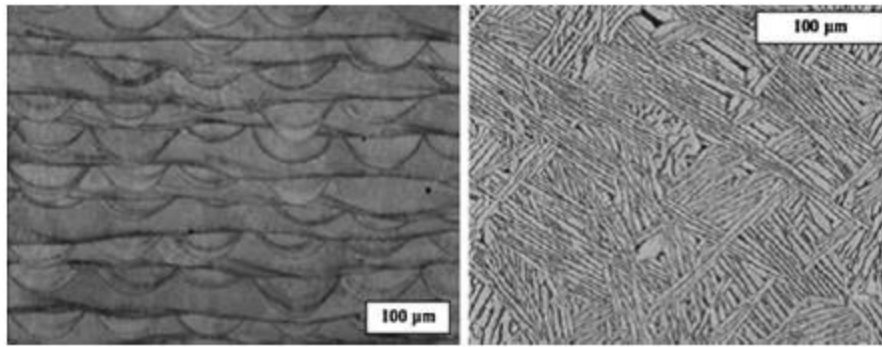


Fig. 5.17 Representative CoCrMo mLS microstructure (*left*, courtesy: EOS), and Ti6Al4V EBM microstructure (*right*, courtesy: Arcam)

MATERIAL EXTRUSION

4.6 Basic Principles

There are a number of key features that are common to any extrusion-based system: –

- Loading of material
- Liquification of the material
- Application of pressure to move the material through the nozzle
- Extrusion
- Plotting according to a predefined path and in a controlled manner
- Bonding of the material to itself or secondary build materials to form a coherent solid structure
- Inclusion of support structures to enable complex geometrical features

4.7 Fused Deposition Modeling from Stratasys

By far the most common extrusion-based AM technology is fused deposition modeling (FDM), produced and developed by Stratasys, USA [7]. FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure. A typical FDM machine can be seen in Fig. 6.6, along with a picture of an extrusion head.

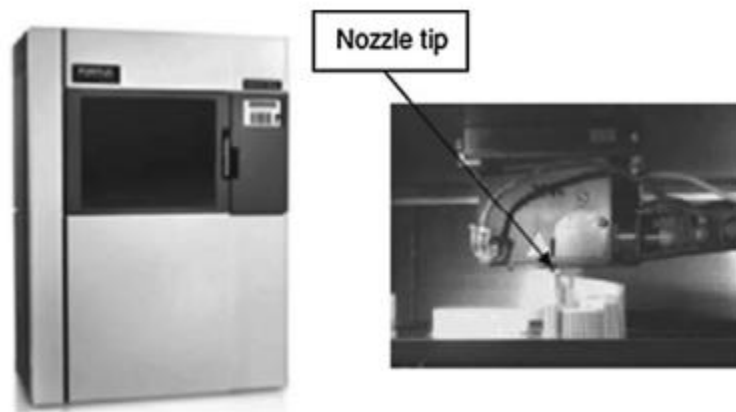


Fig. 6.6 Typical Stratasys machine showing the outside and the extrusion head inside (courtesy of Stratasys)

The initial FDM patent was awarded to Stratasys founder Scott Crump in 1992 and the company has gone from strength to strength to the point where there are more FDM machines than any other AM machine type in the world. The major strength of FDM is in the range of materials and the effective mechanical properties of resulting parts made using this technology. Parts made using FDM are among the strongest for any polymer-based additive manufacturing process.

The main drawback to using this technology is the build speed. As mentioned earlier, the inertia of the plotting heads means that the maximum speeds and accelerations that can be obtained are somewhat smaller than other systems. Furthermore, FDM requires material to be plotted in a point-wise, vector fashion that involves many changes in direction.

4.8 Materials

The most popular material is the ABSplus material, which can be used on all current Stratasys FDM machines. This is an updated version of the original ABS (acrylonitrile butadiene styrene) material that was developed for earlier FDM technology. Users interested in a translucent effect may opt for the ABSi material, which has similar properties to other materials in the ABS range. Some machines also have an option for ABS blended with Polycarbonate (PC). Table 6.1 shows properties for various ABS materials and blends

These properties are quite similar to many commonly used materials. It should be noted, however, that parts made using these materials on FDM machines may exhibit regions of lower strength than shown in this table because of interfacial regions in the layers and possible voids in the parts.

There are three other materials available for FDM technology that may be useful if the ABS materials cannot fulfill the requirements. A material that is predominantly PC-based can provide higher tensile properties, with a flexural strength of 104 MPa. A variation of this material is the PC-ISO, which is also PC-based, formulated to ISO 10993-1 and USP Class VI requirements. This material, while weaker than the normal PC with a flexural strength of 90 MPa, is certified for use in food and drug packaging and medical device manufacture. Another material that has been developed to suit industrial standards is the ULTEM 9085 material. This has particularly favorable flame, smoke, and toxicity (FST) ratings that makes it suitable for use in aircraft, marine, and ground vehicles. If applications require improved heat deflection, then an option would be to use the Polyphenylsulfone (PPSF) material that has a heat deflection temperature at 264 psi of 189 C. It should be noted that these last three materials can only be used in the high-end machines and that they only work with breakaway support system, making their use somewhat difficult and specialized. The fact that they have numerous ASTM and similar standards attached to their materials indicates that Stratasys is seriously targeting final product manufacture (Direct Digital Manufacturing) as a key application for FDM

Note that FDM works best with polymers that are amorphous in nature rather than the highly crystalline polymers that are more suitable for PBF processes. This is because the polymers that work best are those that are extruded in a viscous paste rather than in a lower viscosity form. As amorphous polymers, there is no distinct melting point and the material increasingly softens and viscosity lowers with increasing temperature. The viscosity at which these amorphous polymers can be extruded under pressure is high enough that their shape will be largely maintained after extrusion, maintaining the extrusion shape and enabling them to solidify quickly and easily.

Furthermore, when material is added in an adjacent road or as a new layer, the previously extruded material can easily bond with it. This is different from Selective Laser Sintering, which relies on high crystallinity in the powdered material to ensure that there is a distinct material change from the powder state to a liquid state within a well-defined temperature region

Table 6.1 Variations in properties for the ABS range of FDM materials (compiled from Stratasys data sheets)

Property	ABS	ABSi	ABSplus	ABS/PC
Tensile strength (MPa)	22	37	36	34.8
Tensile modulus (MPa)	1,627	1,915	2,265	1,827
Elongation (%)	6	3.1	4	4.3
Flexural strength (MPa)	41	61	52	50
Flexural modulus (MPa)	1,834	1,820	2,198	1,863
IZOD impact (J/m ²)	106.78	101.4	96	123
Heat deflection at 66 psi (°C)	90	87	96	110
Heat deflection at 264 psi (°C)	76	73	82	96
Thermal expansion (in./in./F)	5.60E – 05	6.7E – 6	4.90E – 05	4.10E – 5
Specific gravity	1.05	1.08	1.04	1.2

4.9 Limitations of FDM

FDM machines made by Stratasys are very successful and meet the demands of many industrial users. This is partly because of the material properties and partly because of the low cost of the entry-level machines. There are, however, disadvantages when using this technology, mainly in terms of build speed, accuracy, and material density. As mentioned earlier, they have a layer thickness option of 0.078 mm, but this is only available with the highest-cost machine and use of this level of precision will lead to longer build times. Note also that all nozzles are circular and therefore it is impossible to draw sharp external corners; there will be a radius equivalent to that of the nozzle at any corner or edge. Internal corners and edges will also exhibit rounding. The actual shape produced is dependent on the nozzle, acceleration, and deceleration characteristics, and the viscoelastic behavior of the material as it solidifies.

The speed of an FDM system is reliant on the feed rate and the plotting speed. Feed rate is also dependent on the ability to supply the material and the rate at which the liquefier can melt the material and feed it through the nozzle. If the liquefier were modified to increase the material flow rate, most likely it would result in an increase in mass. This in turn would make it more difficult to move the extrusion head faster. For precise movement, the plotting system is normally constructed using a lead-screw arrangement. Lower cost systems can use belt drives, but flexing in the belts make it less accurate and there is also a lower torque reduction to the drive motor.

One method to improve the speed of motor drive systems is to reduce the corresponding friction. Stratasys used Magnadrive technology to move the plotting head on early Quantum machines. By gliding the head on a cushion of air counterbalanced against magnetic forces attracting the head to a steel platen, friction was significantly reduced, making it easier to move

the heads around at a higher speed. The fact that this system was replaced by conventional ball screw drives in the more recent FORTUS 900mc machine indicates that the improvement was not sufficient to balance against the cost.

One method not tried outside the research labs as yet is the use of a particular build strategy that attempts to balance the speed of using thick layers with the precision of using thin layers. The concept here is that thin layers only need to be used on the exterior of a part. The outline of a part can therefore be built using thin layers, but the interior can be built more quickly using thicker layers, similar to the cyclic build styles described in Chap. 4. Since most FDM machines have two extruder heads, it is possible that one head could have a thicker nozzle than the other. This thicker nozzle may be employed to build support structures and to fill in the part interior. However, the difficulty in maintaining a correct registration between the two layer thicknesses has probably prevented this approach from being developed commercially. A compromise on this solution is to use a honeycomb (or similar) fill pattern that uses less material and take less time. This is only appropriate for applications where the reduced mass and strength of such a part is not an issue

An important design consideration when using FDM is to account for the anisotropic nature of a part's properties. Additionally, different layering strategies result in different strengths. For instance, the right-hand scanning strategy in Fig. 6.5 creates stronger parts than the left-hand scanning strategy. Typically, properties are isotropic in the x - y plane, but if the raster fill pattern is set to preferentially deposit along a particular direction, then the properties in the x - y plane will also be anisotropic. In almost every case, the strength in the z -direction is measurably less than the strength in the x - y plane. Thus, for parts which undergo stress in a particular direction it is best to build the part such that the major stress axes are aligned with the x - y plane rather than in the z -direction.