Multimaterial powder bed fusion techniques

Mehrshad Mehrpouya, Daniel Tuma and Tom Vaneker
Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands
Mohamadreza Afrasiabi and Markus Bambach
Advanced Manufacturing Lab, ETH Zurich, Zurich, Switzerland, and
Ian Gibson
Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

Abstract

Purpose – This study aims to provide a comprehensive overview of the current state of the art in powder bed fusion (PBF) techniques for additive manufacturing of multiple materials. It reviews the emerging technologies in PBF multimaterial printing and summarizes the latest simulation approaches for modeling them. The topic of "multimaterial PBF techniques" is still very new, undeveloped, and of interest to academia and industry on many levels.

Design/methodology/approach – This is a review paper. The study approach was to carefully search for and investigate notable works and peer-reviewed publications concerning multimaterial three-dimensional printing using PBF techniques. The current methodologies, as well as their advantages and disadvantages, are cross-compared through a systematic review.

Findings – The results show that the development of multimaterial PBF techniques is still in its infancy as many fundamental "research" questions have yet to be addressed before production. Experimentation has many limitations and is costly; therefore, modeling and simulation can be very helpful and is, of course, possible; however, it is heavily dependent on the material data and computational power, so it needs further development in future studies.

Originality/value – This work investigates the multimaterial PBF techniques and discusses the novel printing methods with practical examples. Our literature survey revealed that the number of accounts on the predictive modeling of stresses and optimizing laser scan strategies in multimaterial PBF is low with a (very) limited range of applications. To facilitate future developments in this direction, the key information of the simulation efforts and the state-of-the-art computational models of multimaterial PBF are provided.

Keywords Additive manufacturing, 3D printing, Powder bed fusion, Multimaterial, Modeling and simulation

Paper type General review

1. Introduction

Additive manufacturing (AM), also known as three-dimensional (3D) printing, emerged a few decades ago and has been in the research and development spotlight ever since. It has grown exponentially because of its crucial role in the Fourth Industrial Revolution (Mehrpouya *et al.*, 2019). AM can be characterized by customizable and facile fabrication, actively used in several domains such as aerospace, electronics, robotics and textile (Gibson *et al.*, 2021; Farahani *et al.*, 2016; Gisario *et al.*, 2019). The ISO/ASTM 529000:2015 standard has categorized the AM methods in seven main groups (Wohlers and Caffrey, 2014), including powder bed fusion (PBF), vat photopolymerization (VP), material extrusion (ME), material jetting (MJ), binder jetting (BJ), directed energy deposition (DED) and sheet lamination (SL), as shown in Figure 1. Among these categories, PBF is recognized as one of the most common AM technologies because of its attractive capability of fabricating complex geometries using many possible materials (Sun *et al.*, 2017; Vock *et al.*, 2019).

The majority of the AM techniques fabricate a product using only a single material. However, multimaterial 3D printing is believed to provide a great opportunity for the fabrication of highly complex products that can improve the functional performance of manufactured parts (Bandyopadhyay and Heer, 2018; Mehrpouya *et al.*, 2021). Biomedical engineering, soft robotics and electronics are among the main applications of multimaterial 3D printing technology (Li *et al.*, 2019; Ji *et al.*, 2018; Soreni-Harari *et al.*, 2020; Zhang *et al.*, 2019; Loke *et al.*, 2019; Han and Lee, 2020). This technology has the capability to create a part with a wide range of characteristics by combining various materials in one entity (Gibson *et al.*, 2007). The use of multiple materials in PBF affects the whole process

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chain. Reclaiming powder and recycling the printed artifact are two major challenges of the multimaterial 3D printing process (Wei and Li, 2021; Horn *et al.*, 2020). However, there are more difficulties such as complexity in selective material deposition, issues with co-processing and material interface formation and also developing materials and process modeling. Therefore, the processing of diverse materials necessitates the employment of various monitoring instruments and the integration of electronic systems (Seidel and Anstätt, 2016).

Although various printing techniques, like ME or direct energy deposition methods, can be applied for the fabrication of multimaterial products, the focus of this paper is on multimaterial PBF techniques. This is because of the many benefits of PBF such as the capability for the fabrication of very complex shapes and tiny products with appropriate surface quality using functionally appropriate materials (Gibson *et al.*, 2021; Calignano, 2018). In the following, first, four principal PBF techniques, including selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM) and multi-jet fusion (MJF), will be briefly reviewed. This section also will compare the pros and cons of each PBF technique. Then, the application of PBF techniques for the multimaterial 3D printing process will be discussed based on the latest research studies on this topic. It will be followed by introducing the novel simulation techniques for modeling them, and in the end, future perspectives and recommendations will be outlined for the multimaterial PBF techniques.

2. Powder bed fusion techniques

PBF is an AM technology where thin layers of material powder are distributed over the build locations by a spreader and consolidated due to the thermal energy absorbed from a heat source such as a heated printing head, laser or electron beam. Then, a new layer of material powder is spread over the build location, and this process repeats until a 3D part is produced. As shown in Figure 1, the PBF technique includes four main methods, and the focus of this study will be on SLS, SLM, EBM and MJF systems. In general, a common set of features may be found in all PBF methods. In the following, the process description of SLS will be described as the paradigm approach. It is notable that both SLS and SLM techniques are generically referred to laser-based PBF (or LPBF process). For the other PBF techniques, a comparison will be made with the paradigm approach.

2.1 Selective laser sintering

The SLS process used a high-power laser for sintering selectively the powdered material. In this technique, the heat treatment process is used to the material during the sintering process and transforms the powders into coherent solids at temperatures below their melting points (Awad *et al.*, 2020; Shirazi *et al.*, 2015). To reduce the degradation and oxidation of the powdered material, the SLS process is carried out inside an isolated environment supplied with nitrogen gas. In some SLS processes, infrared heaters or build-in resistive heaters in the build platform are used to maintain the temperature of the powder material just below the glass transition temperature. Also, pre-heating has the advantage of using less laser energy for fusion and reducing the chance of the component warping owing to non-uniform thermal expansion and contraction. Preheating also minimizes the residual stresses in the sintered powder (Shen *et al.*, 2021; Kemerling *et al.*, 2018).

During the SLS printing process, first, thin layers of powdered material (typically 0.075–0.1 mm) will be dispersed across the build area supplied by the feed platform (Gibson *et al.*, 2021). The remaining powder is collected in the collection area. Once a powder layer has been formed, the laser beam scans the powders selectively and fuses/sinters the first powder particle layer. The beam scans are based on 3D computer-aided design (CAD) data from the created model. Then, the fabrication piston can move down by the required thickness to which the following thin powder particle layer will be dispersed across the build area by a powder roller. Then, a laser beam scans the powder selectively and fuses/sinters the second powder particle layer onto the first layer. This process repeats itself until a complete predefined 3D part is produced. Figure 2 illustrates the SLS process and associated components.

2.2 Selective laser melting

The SLM procedure is quite similar to the SLS procedure. The SLM goes further by using a power source (e.g. high power laser) for a fully homogeneous melted powder, which for the SLS process, the powder was merely fused. As a result, the material processing is different for both techniques as the SLM technique is mainly applied for metal alloys (e.g. stainless steel, aluminum, titanium), while the SLS process is mostly used for ceramics, glass and plastics; however, they are not limited to only these materials (Yan *et al.*, 2020; Sing *et al.*, 2017; Yap *et al.*, 2015; Singh *et al.*, 2016). There is also a difference in design aspects concerning both methods. SLM, unlike SLS, is difficult to manage because melting the powder particles requires a high energy input from the laser beam (Papadakis *et al.*, 2018). Concerning the quality aspects, SLM is a proven technology where parts are manufactured with high density (Lin *et al.*, 2019), which can be further processes as any welding part like heat treatment processes (Fergani *et al.*, 2018a; Fergani *et al.*, 2018b) or hybrid manufacturing (Costa *et al.*, 2021; Bambach *et al.*, 2020b, 2021). On the other hand, the tolerance and surface finishes are limited.

2.3 Electron beam melting

EBM process can be described as a process where the powder is melted by the use of a high-energy electron beam instead of a laser beam or other heat sources (Körner, 2016). Because the materials must be electrically conductive to release the absorbed electrons, the electron beam can only be used for metals. The EBM process takes place in a vacuum environment to prevent contamination and oxidation of the powder and the final product in the fabrication process. Thin layers of powdered material, supplied by powder hoppers, are spread across the build plate by a rake. Afterward, the spread powdered material is preheated to prevent powder blown and spheroidization phenomena (Arnold *et al.*, 2018). Powder blown emerges from the loose powder particles that can be easily pushed away due to the impact of the high energy in the EBM process (Weiwei *et al.*, 2011). Also, low temperatures surrounding the molten pool and poor wetting qualities between powder particles cause spheroidization, which results

Figure 1 Tree diagram of AM techniques including PBF techniques, where (C) ceramic, (F) food, (M) metal, (L) live cells, (O) organic material, (P) polymer, (S) sand and (W) wax

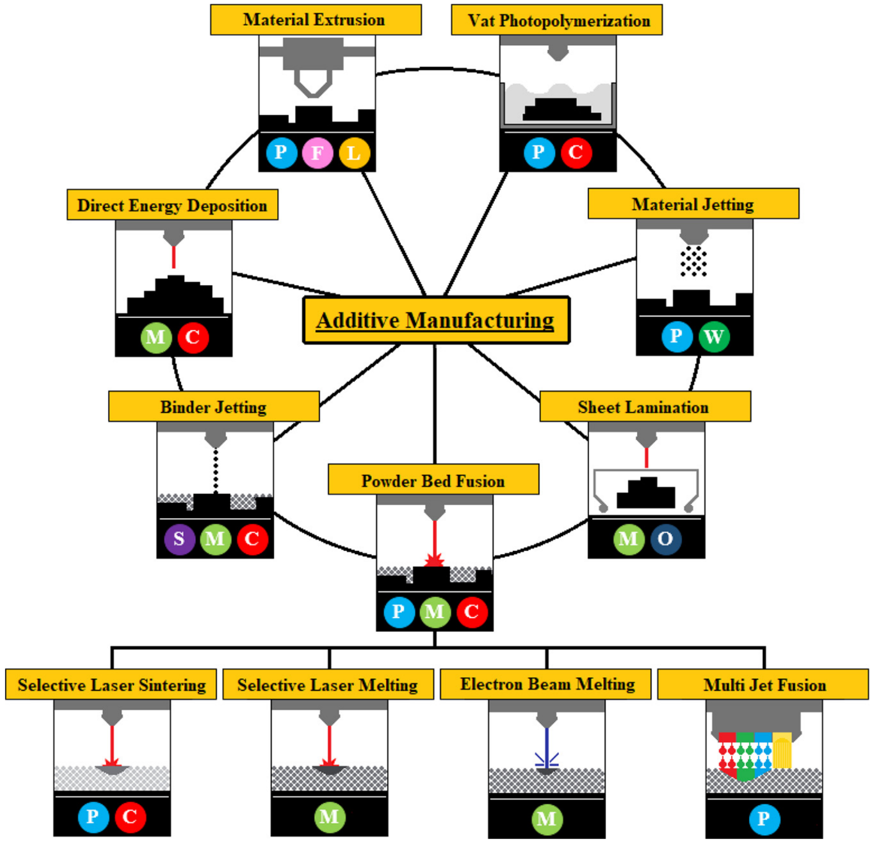
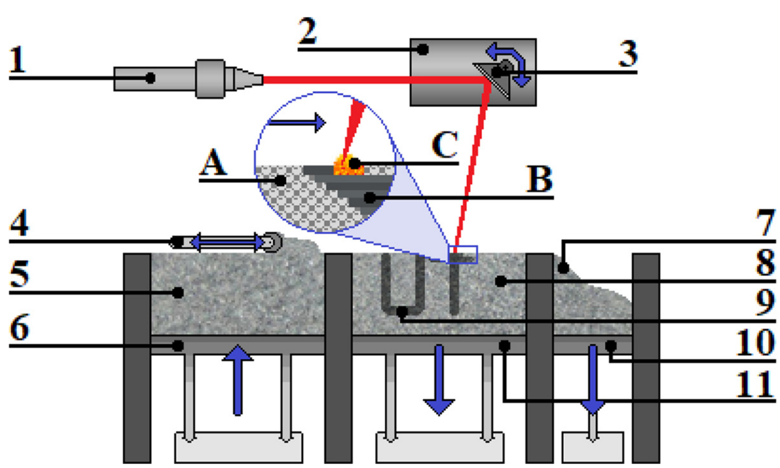


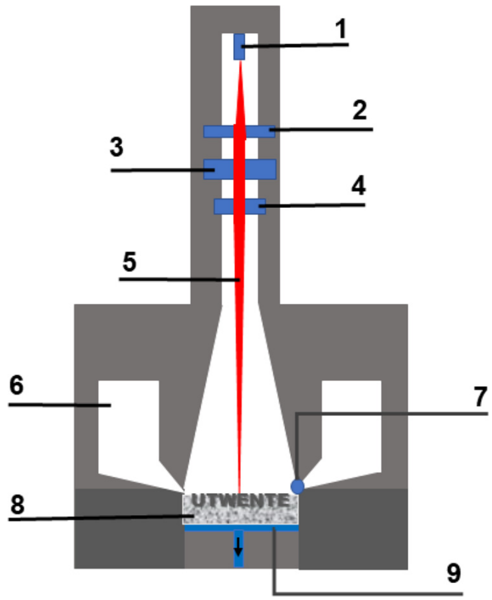
Figure 2 A schematic of SLS/SLM process where (1) laser source, (2) scanning system, (3) scanning mirrors, (4) powder roller, (5) powder supply, (6) feed platform, (7) collected powder, (8) powder bed, (9) sintered powder, (10) collection platform, (11) build platform, (a) unsintered material, (b) sintered powder particles and (c) laser sintering process



in forming failure or poor precision (Xu *et al.*, 2020). Following the EBM processing steps, the preheated powder will be melted in selected areas based on the predefined CAD model using a high-energy electron beam. Similar to other PBF processes, the build platform moves down, then the next layer is deposited and fused with the previous layer. This process repeats itself until a complete specific 3D part is produced (Galati and Iuliano, 2018). Figure 3 illustrates an EBM machine introducing various sections.

There are some similarities between EBM and SLM processes. Both of them are working based on layer-by-layer technology and melt the powder above the melting point.

Figure 3 Component overview of an EBM machine, where (1) electron gun, (2) magnetic lens, (3) focus lens, (4) deflection lens, (5) electron beam, (6) powder feeder, (7) roller, (8) powder, (9) build platform



However, there are also some differences between the two processes (Wong and Hernandez, 2012). In the EBM process, an electron beam is used instead of a laser to fuse and melt the powder particles. An important benefit between the EBM and SLM process is the high efficiency of the beam. Indeed, EBM has a more efficient way of generating energy for the power source, which leads to lower energy consumption as well as lower maintenance and installations costs (Ulf Lindhe, 2003). Moreover, the EBM process has more process parameters than SLM (e.g. beam power, scanning velocity, beam focus, beam diameter, plate temperature, preheat temperatures) (Gokuldoss *et al.*, 2017), while EBM has a limited range of materials in comparison with SLM. But, it has the capability of processing brittle material that cannot be processed by SLM (Zhao *et al.*, 2016; Zhao *et al.*, 2020; Gong *et al.*, 2015).

2.4 Multi-jet fusion

MJF is another PBF technique that can be applied for the fabrication of a functional product with an accurate dimension. The benefit of this technology is to not require support structures, which makes it suitable for producing complex geometries without the extra time and additional costs (O'Connor *et al.*, 2018). The MJF process can be described as where a bed of material is selectively fused through the addition of a binding agent and a heat source normally ultraviolet (UV) or infrared (IR) lights (O'Connor and Dowling, 2020). Figure 4 exemplifies the whole manufacturing process of the MJF technique. The process first starts with a layer of powder that is evenly distributed and uniformly preheated on the powder bed. A fusing agent is ejected by the print head selectively onto the layer of powder where the particles need to be melted. The detailing agent is a second agent that prevents sintering and is deposited around the contours of the part to increase resolution and ensure that the sharp edges of the part are printed properly. Next, IR/UV light lamps are then moved over the powder bed and heat the fusing agent regions. As a result, the powders in these areas are melted and glued together. Once one layer is finished, the powder is distributed on top of the previous layer, and the process is repeated until the final part is fully made. The component is always encased in loose powder after it is done, which must be removed. To achieve an aesthetically pleasing surface, the component can be bead blasted and also dyed black. Figure 4 illustrates a schematic overview of the MJF process.

MJF is an excellent choice if parts with excellent mechanical properties, dimensional precision and high resolution are needed (Mele *et al.*, 2020). It can also be applied for various types of material, including polymers, metals and ceramics. Currently, HP MJF is a well-known MJF machine on the market that applies for low to medium batch production with a high printing speed. For the metal printing process, the fabricated parts need an additional sintering process in the oven to achieve the maximum density (HP, 2018).

Table 1 summarizes the most important advantages and disadvantages of the PBF techniques, including SLS, SLM, EBM and MJF processes.

Figure 4 The MJF process, where (1) heating lamps, 2) fusing agent print heads, (3) powder bed and printed parts, (4) build platform, (5) powder supply, (6) scraper, (7) fusing lamps, (8) detailing agent print heads, (9) thermal camera, (10) printed parts, (11) powder lift screws, (a) powder is spread, (b) applying fusing and detailing agents, (c) exposing to UV/IR-light and (d) non-fused powder and fused layers

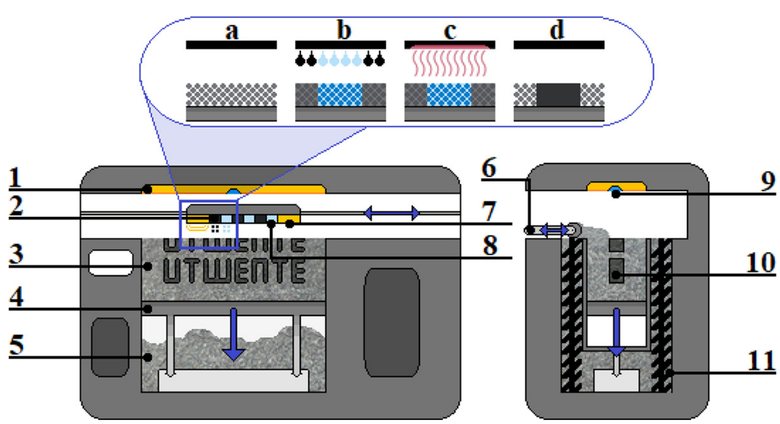


Table 1 Overview of the advantages and disadvantages of the PBF techniques

Techniques	Advantages	Disadvantages	References
SLS	⊕ Use a wide range of materials	⊖ Lower-quality metal parts than EBM parts	Rafiee et al., 2020; Dev Singh et al., 2021
	⊕ Parts are cheaper than EBM parts	⊖ Needs additional post-heat treatment to rough surfaces	
	⊕ Design freedom because support structures are not required	⊖ Relatively high cool-down time	
	⊕ High level of accuracy	⊖ Susceptible to shrinkage and warping	
SLM	⊕ Complex shapes	⊖ Requires post-heat treatment due to stresses	(Rafiee et al., 2020)
	⊕ Use a wide range of materials	⊖ Relatively slow process	
	⊕ Tune properties during processing	⊖ Relatively expensive	
	⊕ Manufacture parts with high density	⊖ Acute size restrictions	
	⊕ Excellent mechanical properties of the 3 D object	⊖ Difficult to control process	
	⊕ Design freedom because support structures are not required	⊖ Limited tolerance and surface finishing	
		⊖ Susceptible to shrinkage and warping	
EBM	⊕ Can process brittle material that cannot be processed by SLM/SLS	⊖ Relatively expensive process	(Rafiee et al., 2020; Wong and Hernandez, 2012)
		⊖ Limited range of materials	
	⊕ Higher efficiency in generating beam in comparison with SLS and SLM	⊖ Needs additional post-processing to rough surfaces	
	⊕ Oxidation-reduction to vacuum	⊖ Only conductive alloys can be obtained	
	⊕ Lower power consumption than SLM	⊖ Lower level accuracy compared to SLM	
	⊕ Design freedom fewer build supports	⊖ High fatigue	
	⊕ Efficiency in terms of waste and maximizing strength		
MJF	⊕ High production speed	⊖ Limited range of materials	(Rafiee et al., 2020; Ulf Lindhe, 2003; Gokuldoss et al., 2017)
	⊕ Complex shapes		
	⊕ High (post-) process automation	⊖ High-performance polymer currently prioritized	
	⊕ Efficiency in terms of waste and strength		
	⊕ Surfaces and details		
	⊕ Full-color printing		

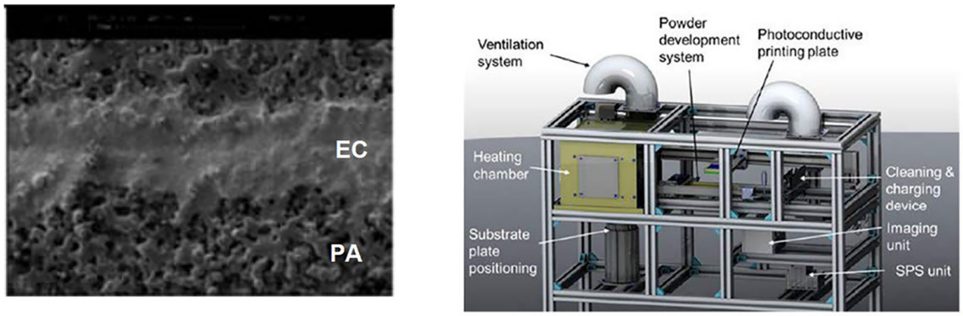
3. Multimaterial powder bed fusion techniques

The multimaterial process can be described as where multiple materials are used (in a single process) for fabricating a 3D part (Thompson *et al.*, 2016; Vaneker *et al.*, 2020; Gibson *et al.*, 2007; Mohammed *et al.*, 2021). But, the use of multiple materials in a powder affects the whole process chain (Wei and Li, 2021; Chen *et al.*, 2020b). This is due to the fact that the preprocessing parameters will be affected due to multiple materials in the powder and new scan strategies have to be developed (Binder *et al.*, 2018; Schneck *et al.*, 2021; Walker *et al.*, 2021). But overall, the use of multiple materials has many advantages. It creates opportunities to combine different material properties that can be obtained during one single printing process. Powder cohesion can almost be avoided (e.g. as "build" powder a polymer and as "support" powder a ceramic or different polymer), which prevents inaccurate part dimensions and poor surface finish (Rafiee *et al.*, 2020). Moreover, structure complexity is further increased because different materials can be used (Yusuf *et al.*, 2021); therefore, new material properties could arise that can affect positively the mechanical resistance. With multimaterial powder deposition, cheaper powders can be used to provide mechanical support during the building process (Arnold *et al.*, 2018); as a result, this can replace the more expensive powder, which leads to a decrease in wastes.

3.1 Multimaterial selective laser sintering

SLS is one of the AM techniques that can print multiple materials in the same printing process (Laumer *et al.*, 2012). Gibson *et al.* (2000, 2002) were a pioneer group that developed the SLS technique with the application of multiple materials in the printing process. They applied various strategies to improve the properties of the SLS fabricated part by adding the second material to the process. This so-called functional gradient multimaterial (FGM) method can be applied for achieving desired properties or functions. Figure 5 shows an SEM image of the SLS fabricated part using polyamide (PA) polymer with a path of an electrical conductive (EC) material on top of it. In another study, Sigmarsson *et al.* (2006) reported the possibility of the application of the SLS printing process for the fabrication of multilayer microelectronic components with varying properties, such as metals and dielectrics. In this process, a laser sinters different material powders to fabricate the final product and the remaining unsintered powder is then collected. This will continue until the layer-on-layer setup metal–insulator–metal (MIM) is achieved. Stichel *et al.* (2018) reported a particular technique using electrophotographic powder transfer for the multimaterial SLS printing process. For this purpose, they made a particular experimental setup [Figure 5(b)], including two chambers designed for transferring the

Figure 5 (a) SEM image of sintered PA polymer with a path of electrically conductive material on top, reproduced from Levy *et al.* (2003), (b) a schematic of the design SLS machine for printing multiple materials (Stichel *et al.*, 2018)



positively charged powder to the substrate in a typical SLS process. The results proved the benefit of this process in the multimaterial powder deposition process, as well as for uniform powder distribution in the SLS process.

A few years ago, the Belgian-based company *Aerosint SA* developed the first multimaterial SLS process that can selectively deposit two or more powders in a single layer (Eckes, 2018b). This low-waste multimaterial SLS process is compatible with ceramics, metals and polymer powders. *Aerosint SA* provides powder via a recoater consisting out of patterning drums. Each drum contains one unique material that spreads specifically the fine powder voxels layer by layer over the build area. Once a proper powder layer has been formed, the laser sinters uniformly the powder to the required temperatures; then, this process repeats itself until a complete specific 3D part is produced. Figure 6(a) shows how the *Aerosint* powder deposition head can be used for the multimaterial printing process.

According to Aerosint, using multimaterial SLS brings several areas of opportunity such as local optimization of mechanical properties (e.g. wear resistance, vibration damping, strength) and improved chemical and physical performances (e.g. aesthetics, electrical and thermal conductivity, corrosion resistance). Therefore, it can be applied for a wide range of applications, including aerospace, automotive and medical domains. A proof sample from the multimaterial SLS process is shown in Figure 6(b), where the black material is carbon-black colored PEEK powder and the white co-deposited material is aluminum oxide powder.

In 2020, Whitehead and Lipson developed a method for printing multimaterial components using SLS technology with an inverted laser and clear glass plates (Whitehead and Lipson, 2020). Figure 7(a) exemplifies the setup of the laser source, mirrors and the build plate. In this approach, the laser is pointed upward through the clear glass plates, as can be seen in Figure 7(b). Therefore, thin layers of powder are coated onto the glass plates instead of a powder bed. The laser is guided through a bottom glass plate to fuse the coating. The layer with the selectively bonded material is then lifted and moved to another plate, which is covered with a different material. This process is repeated multiple times until a multimaterial sample is obtained, as shown in Figure 7(c). This printing setup eliminates the demand for a large powder bed for the fabrication process but also allows for sintering various powders in a single bed. This figure also shows the final fabricated part, which is a combination of thermoplastic polyurethane powder (TPU) and nylon as a proof of concept. The presented sample is made of 50 layers, each with a thickness of 2.18 mm.

3.2 Multimaterial selective laser melting

Within the past years, several studies have been carried out regarding the usage of multimaterial in the SLM process (Wits and Amsterdam, 2021; Mei *et al.*, 2019; Rankouhi *et al.*, 2021). It can be understood from the literature survey that multimaterial SLM is not just a straightforward step after a

Figure 6 (a) Schematic overview of the patented Aerosint SA selective powder technology (Aerosint, 2020) and (b) Created sample with the SLS technique, reproduced from Eckes (2018a)

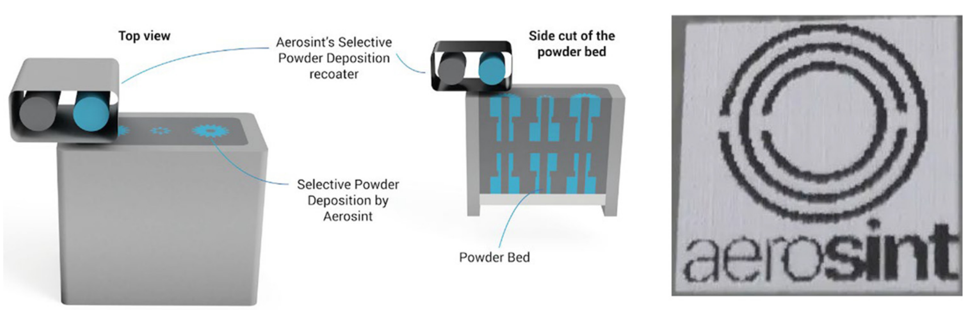
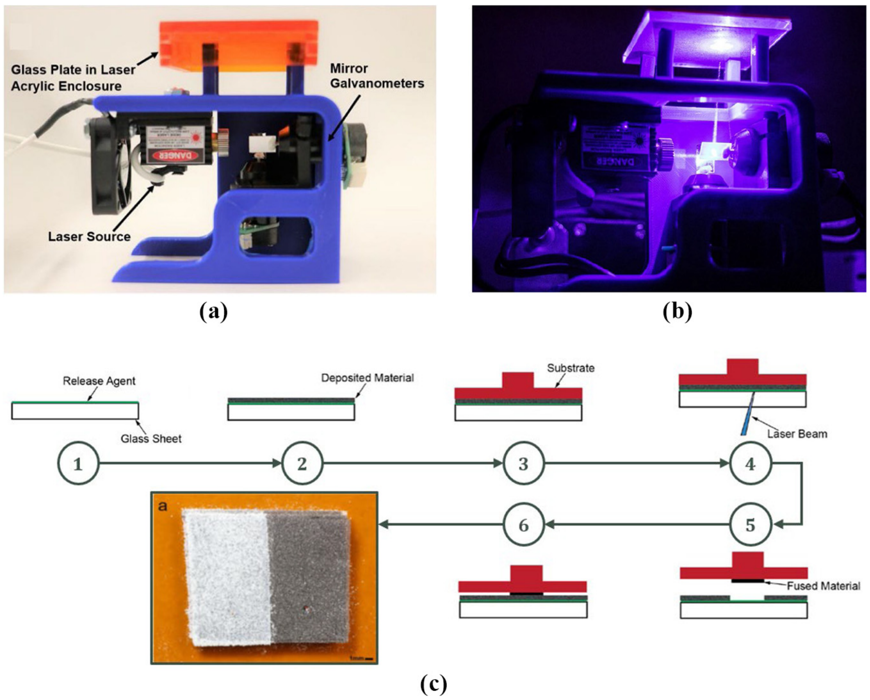


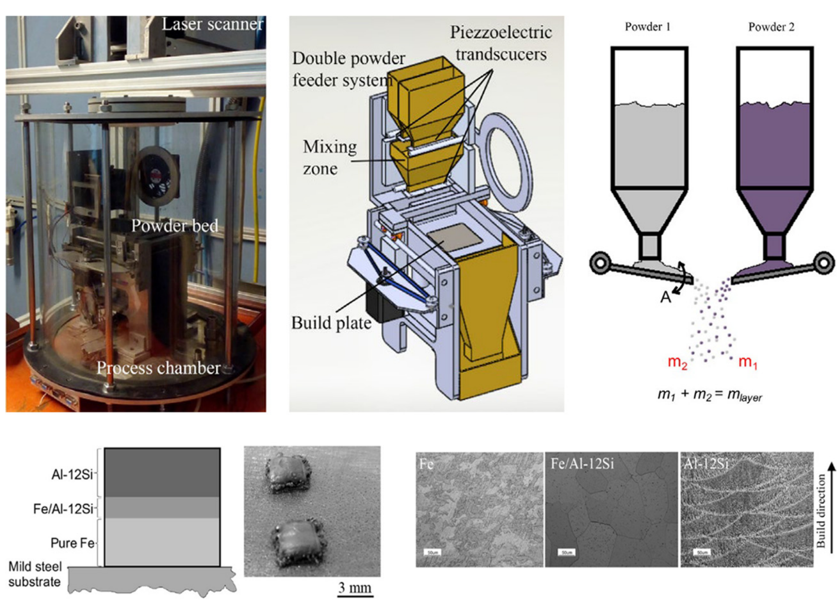
Figure 7 (a) Schematic of the SLS technology with an inverted laser system for printing multimaterial components, (b) The applied laser setup during the experiment and (c) Overview of the inverted sintering process; (1) the green agent is distributed over the glass sheet, (2) unfused gray material is distributed over the green agent, (3) the substrate is attached on top of the deposited material, (4) the laser beam is irritated over the pre-programmed pattern, (5) the fused material is easily removed from the surface, (6) the process is repeated with a new layer for completing the multilayer product and (7) the fabricated multimaterial sample, reproduced from Whitehead and Lipson (2020)



mono-material process, but rather a completely new topic that requires comprehensive and original research. A few research groups active in this field have studied some important aspects of this process, which are reviewed in the following.

Demir and Previtali (Demir and Previtali, 2017) demonstrated a multimaterial SLM system prototype, namely, *Powderful*, that is capable of mixing two metallic powders at different compositions on-demand, as shown in Figure 8(a), where a

Figure 8 (a) Schematic of Powderfull multimaterial SLM system, (b) overview of the double powder feeder system, (c) design of powder feeder system using two powders and (d) deposition specimen from the used materials during the process with corresponding cross-sectional of the different material layers, reproduced from Demir and Previtali (2017)



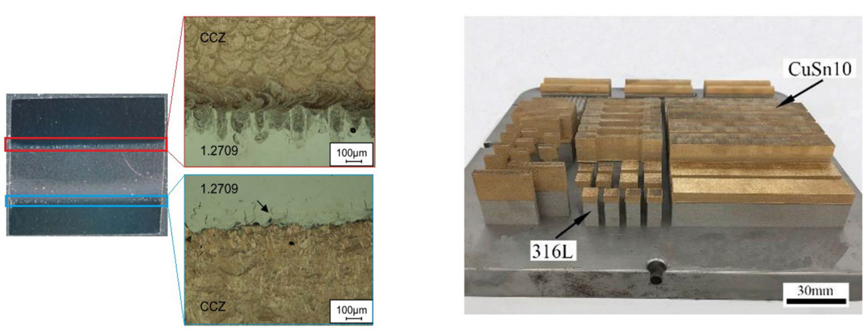
double powder feeder was installed in the system. Figure 8(b)–(c) illustrates the powder distribution system including two powder hoppers with distinct powder material on the top and a mixing system on the bottom. The upper hoppers could be used individually to process a single powder material or in tandem to combine two powder materials to the required composition. In this way, it can precisely create a multimaterial surface in a single layer, which is a combination of two powders with different ratios. Figure 8(d) demonstrates successfully 3D printed Fe/Al-12Si multimaterial components with different materials. However, the results revealed some difficulties in connecting the materials. As can be seen, material microstructures from the deposited materials for various parts of the fabricated sample are collected independently. The result proved that the multimaterial SLM machine has the ability to control and progress the formation of layers with various chemical compositions. It might also be concluded that this technique can be used for multimaterial 3D printing where material variations between layers are needed (Bai *et al.*, 2021). Anstaett *et al.* (2017), Anstaett and Seidel (2016) studied the effects of various material properties on the printability of the multimaterial 3D printing process. They presented a methodical approach showing the procedure for building a 3D multimaterial part concerning the SLM process. Figure 9(a) shows a cross-section of the fabricated steel and CuCr1Zr (CCZ) multimaterial sample. As visible, steel alloy is deposited in the middle of the samples, while CCZ is on top and bottom. This image discovers the influence of the solidification order on forming cracks in the steel in the multimaterial fabricated part. In another study, Chen *et al.* (Chen *et al.*, 2019b) investigated the fabrication of 316 L/CuSn10 multimaterial bimetallic structures, produced by the SLM machine. For that, the SLM printer was equipped with two sets of powder feeding systems designed outside the building chamber and controlled by a powder flow regulator. Various process parameters are considered to evaluate the elemental diffusion and the material mixing in the melt pool of the powders. The samples were printed based on a predefined process setting and scanning strategies. As shown in figure 9(b), the steel part was fabricated before bronze because bronze requires higher energy input compare to steel, and this is due to higher thermal conductivity and lower absorption rate at the laser. Then, the fabricated samples were evaluated by cross-sectional analysis, i.e. scanning electron microscope (SEM) and optical microscopy and some mechanical tests. The authors concluded that the fabricated structures showed good mechanical strength, and the applied scanning strategies were very helpful to improve the bonding between the interfacial layers.

In a preliminary study of the ETH Zurich group, multimaterial specimens of stainless steel (316 L) and CuCrZr were produced via the *Aconity SLM* system (Figure 10). This printer is equipped with the *Aerosint* powder deposition head, as described in Figure 6. As can be seen on the bottom right of this image, the interface is diffused but contains no cracks or voids in layered specimens. In specimens with vertical interfaces, copper diffuses into the steel and causes cracks along grain boundaries under the solidification and shrinkage stresses. The results show that vertical interfaces (and interfaces at an angle) may require advanced multilaser exposure strategies in multimaterial SLM to avoid defects and generate sound interfaces.

In another study, Chueh *et al.* (2020) used an exclusive multimaterial LPBF machine to print copper alloy powder (Cu10Sn) and Nylon powder (PA11). Figure 11(a) exemplifies the setup of the LPBF machine, including the parts for metal and polymer materials. In this process, a layer of polymer powder is dispensed onto the build platform using an ultrasonic vibration-assisted nozzle (UVAN) in accordance with the component geometry on the build platform. A powder-removing nozzle on the UVAN clears residual powder from the printing platform, allowing the metal powder to be dispensed based on the geometry on the same layer. A pneumatic powder-leveling blade was then used to level out the loose powder. The latter steps correspond to Steps 1 to 4 in Figure 11(b). Following that, a laser beam was used to scan the pre-laid powder (metal and polymer) layer selectively using various processing settings. The CAD model is then used as the reference pattern. The build platform was finally lowered to print the following layer. Again, the UVAN dispenses the powders and repeats the aforementioned Steps 5 to 7 until the final multimaterial component is created. Figure 11(c) shows the fabricated sample made of Cu10Sn and PA11 materials.

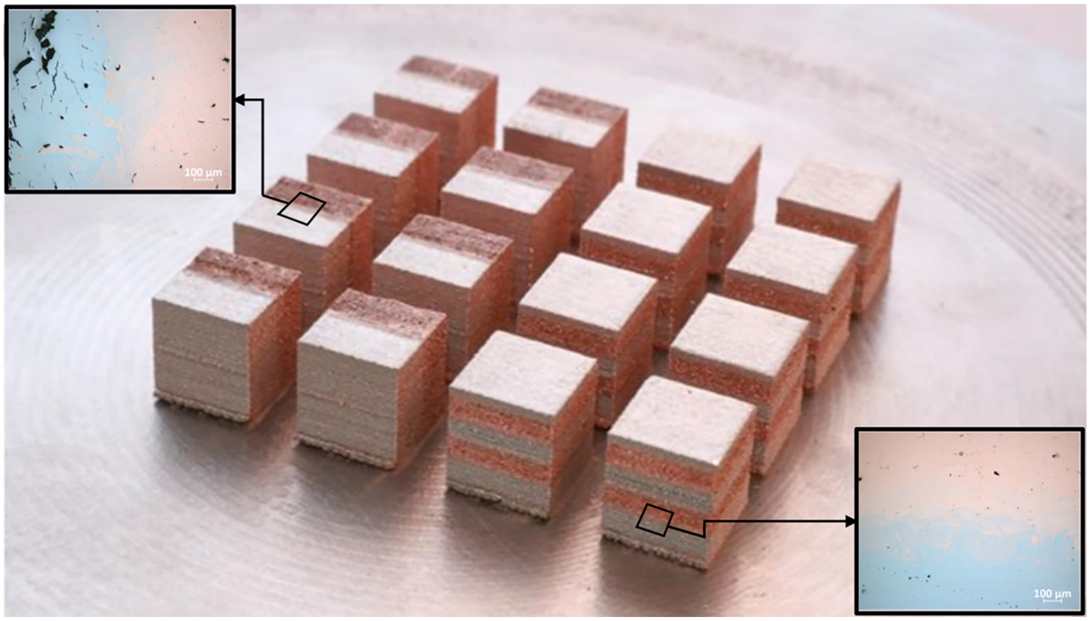
The techniques for hatching a sliced CAD design onto each layer are just as important as the flowrate and stability of powder dispensing. The quality and evenness of the final powder pattern on each layer are influenced by nozzle motions

Figure 9 (a) Cross-sections of 2D multimaterial transitions in build-up direction for CCZ-S-CCZ compound. Arrows show the creation of cracks in the steel area on the component, reproduced from (Anstaett *et al.*, 2017) and (b) the 3D printed multimaterial 316 L/CuSn10 samples fabricated by Dimental-300 SLM machine, reproduced from Chen *et al.* (2019b)



(a) (b)

Figure 10 Preliminary experimental work on multimaterial SLM (316 L+CuCrZr). The image of the cubes is reproduced with permission from Aerosint and the micrographs are taken at ETH Zurich



(Ding *et al.*, 2015). During the study, the researchers discovered that the polymer adjacent to the metal part may melt and/or decompose during laser scanning, covering the metal surface. Such material contamination is a critical issue when both metal and polymer powders are applied during the process and can be a problem and should be avoided. During the printing process, an "appropriate distance" between the two materials should be maintained. The attached carbon residue to the Cu10Sn surface causes balling. This balling would disrupt the subsequent Cu10Sn layer printing stages. The surface roughness can be improved when it is printed with a moderate addition of PA11. The authors concluded that the contamination between the materials is a limitation for printing multimaterial, and that further research is needed.

3.3 Multimaterial electron beam melting

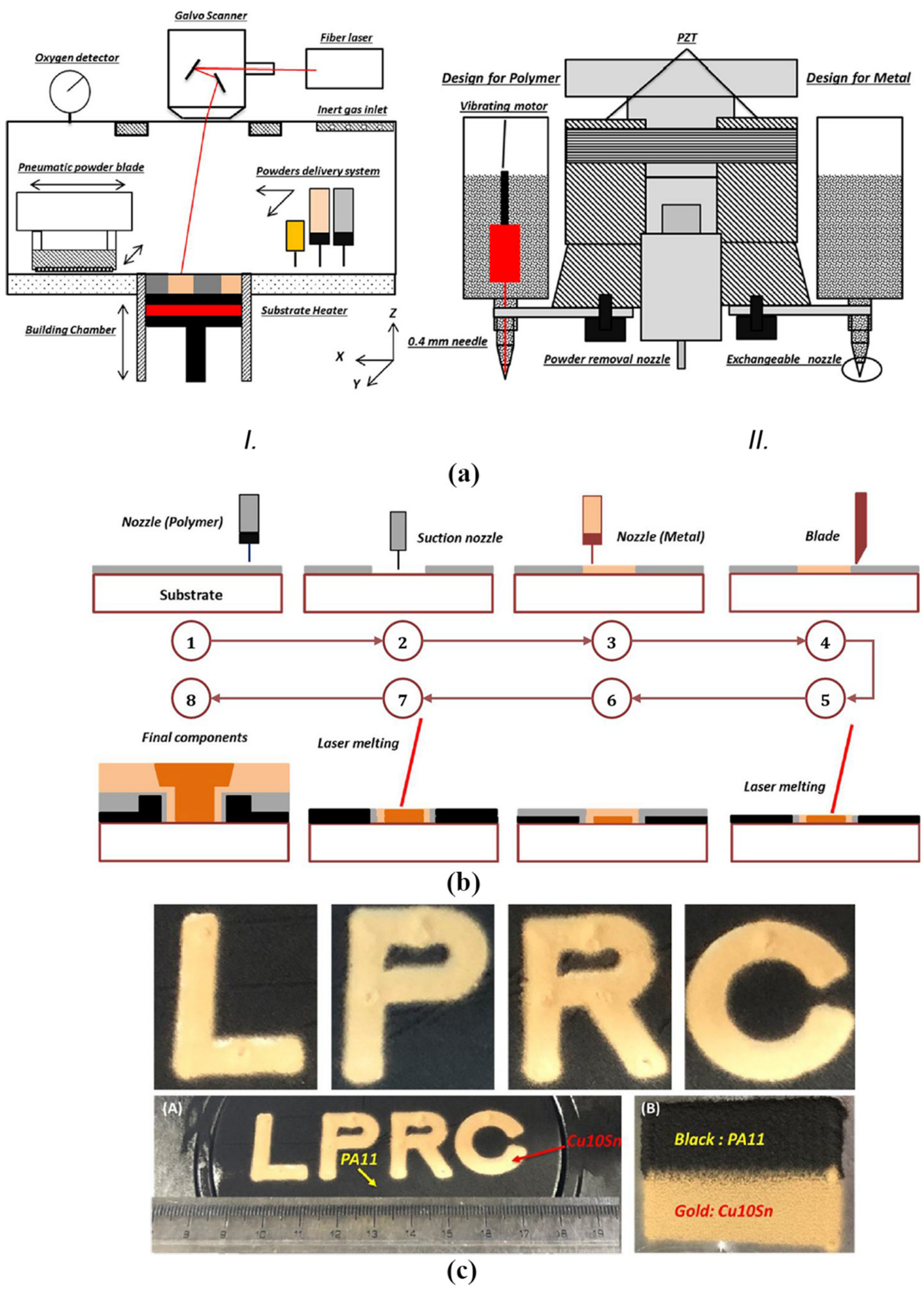
In 2014, Terrazas *et al.* (2014) fabricated multimaterial Ti-6Al-4V and copper samples via *Arcam A2* EBM system. This system is designed to process only one single material at a time. To accommodate both materials, multiple build sequences were established as part of a new methodology. In particular, two build plates were considered in this method for the fabrication of the multimaterial component. Figure 12 exemplifies a summary of the steps in this new process where first the Ti-6Al-4V part is fabricated, then a copper mask plate is fabricated, using computer numerical control (CNC) machining and set up with the fabricated Ti-6Al-4V components (as shown in Steps 1–4). Finally, the copper upper halves are created with the EBM process and complete the multimaterial Ti-6Al-4V and copper component.

The obtained results showed some differences in the hardness and the microstructure of copper and Ti–6Al–4V may arise as a result of the processing conditions used to fabricate multimaterial EBM components. These differ from the standard EBM process that is used to fabricate with single materials. Because of the advantages provided by EBM processing, extensions of the described methodology can become very helpful for the repair of metal parts. Recent studies showed the usage of EBM technology as a way for manufacturing multimaterial metallic components, such as stainless steel, copper, Inconel 718 and some more (Zhang *et al.*, 2021). For example, Hinojos *et al.* (2016) fabricated Inconel 718 and stainless steel 316 L parts using the EBM technique. They reported the joint part had a superior metallurgical quality compared to the classic welding method, which is due to the application of the protective gas resulting in limited contamination of nitrides and oxides. Also, the experiment revealed a minimal thermal effect in the manufacturing process, which has a direct influence on the microstructure and quality of the joint parts.

The literature review presented in Sections 3.1–3.3 reveals numerous challenges and open questions that still need to be addressed in current applications of multimaterial PBF. The key points of this study are summarized in the following:

- Most available works focus on simple bi-metal laminates. Fabrication of fully functional parts using multimaterial PBF is not found.
- Limited work has been done on proposing strategies to avoid insufficient metallurgical bonding and residual stresses at multiphase material interfaces, e.g. Bartolomeu *et al.* (2021).
- Spatter can cause cross-contamination. The current state of the art in multimaterial PBF lacks a framework for detecting and preventing this unwanted phenomenon during the process. Relevant investigations carried out by Chen *et al.* (2019a, 2020a), Liu *et al.* (2014), Sing *et al.* (2015) focus on this issue.
- Controlling the process during multimaterial PBF is a very demanding task due to the miscibility and wetting constraints of different materials and the differences in their properties (e.g. thermal conductivities and expansions, melting points and so on).

Figure 11 (a) A schematic overview of the applied LPBF printing machine and the UVAN system for feeding the material powder in building platform, (b) all applied steps in the LPBF printing process in this method and (c) the final printed objects made of Cu10Sn and PA11 materials, reproduced from (Chueh *et al.*, 2020)



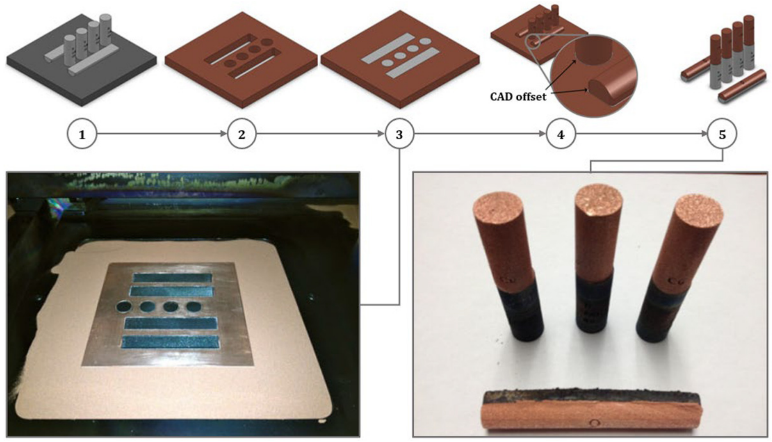
- *In-situ* alloy formation at the interface between different powder fractions is rapid and far from an equilibrium state.
- Defects at grain boundaries (e.g. crack) can occur due to interdiffusion between different materials in multimaterial PBF.

For increasing the reliability of parts fabricated by multimaterial PBF techniques, an essential undertaking is to provide a digital process chain with the help of numerical modeling. Although mostly lacking in rigor and very limited in number, simulation methods for the prediction of stresses and optimization of laser scan strategies in multimaterial PBF have been developed by a few research groups. Section 4 gives an overview of these developments.

4. Simulation of multimaterial powder bed fusion techniques

In essence, a PBF process can be seen as a thermo-mechanical initial boundary value problem, including rapid phase changes

Figure 12 The manufacturing steps in the EBM process, including the image of the build platform and the fabricated Ti-6Al-4V/copper parts, reproduced from Terrazas *et al.* (2014)



and multiple phenomena occurring in the melt pool such as convection, surface tension gradients (Marangoni and capillary effects), vaporization, recoil pressure and momentum losses in mushy zones (de La Batut *et al.*, 2017; Bambach *et al.*, 2020a). Modeling this multiplicity of complex physical phenomena even for a mono-material PFB is a daunting task fraught with many pitfalls, let alone for multimaterial cases. In a comprehensive review paper published in 2015, King *et al.* (King *et al.*, 2015b) provided a good summary of fundamental challenges in understanding the PBF process from the materials and computational perspectives. The authors focused on the computational modeling aspects of metal PBF in their next review paper (King *et al.*, 2015a), concluding that physics-based models of these processes are essential to the broad adoption of AM of metals. There have also been several excellent studies that have reviewed the multiscale modeling and simulation details of powder-based AM applications, among which the articles written by Smith *et al.* (2016) and Markl and Körner (Markl and Körner, 2016) are worthwhile to mention.

With the focus of AM simulation recently shifting from macro-scale studies to meso- and micro-scale analyses, providing a detailed prediction of the melt pool behavior in PBF has become more important and received much attention in the past few years. Using an in-house code called ALE3D, Khairallah and his co-workers (Khairallah *et al.*, 2016) at the Lawrence Livermore National Lab presented a high-fidelity powder-scale model to investigate the significant effects of recoil pressure and Marangoni convection on melt pool dynamics. A year later, Heeling *et al.* (2017) from ETH Zurich developed an efficient 3D model of SLM, validated their numerical model by various experimental test cases and concluded the significance of evaporation effects on the melt pool dynamics. The efficiency in their melt pool simulation framework relies on coupling a finite difference method with a combined level set volume of fluid (CLSVoF) technique for resolving the thermal and fluid flow calculations. The number and diversity of melt pool simulation efforts in mono-material PBF problems are overwhelming (Cook and Murphy, 2020), and examining them is outside the scope of this paper. The literature survey reveals that almost all published works on PBF simulation have relied on mono-material processes, except for a very few efforts, which are reviewed in the following.

Preliminary works on modeling the multimaterial PBF process exist and date back to the early 1920s, including a thermomechanical FEM model to compute residual stresses and distortion in a Ni-dental porcelain part by Dai and Shaw (Dai and Shaw, 2001; Dai and Shaw, 2004). More recently, Sorkin *et al.* (2017) used an adaptation of a molecular dynamics (MD) model to simulate the melting of a layer of Al nanoparticles on top of a layer of Fe nanoparticles. While these primitive multi-material simulations generated valuable insights into a better understanding of the process, the fidelity of their modeling frameworks is far from high due to multiple reasons. For instance:

- the physical model is oversimplified as multiple crucial phenomena such as phase change, Marangoni convection and recoil pressure are neglected;
- a detailed prediction of melt pool behavior is not provided; and
- computations are carried out in low resolution.

It would not be until 2020 that considering multiple materials in the high-fidelity simulation of PBF was attempted by a few research groups. Upon a literature survey, it turns out that the main publications in this field are stemmed from three institutions listed in Table 2.

Through collaborative work between Cardiff University and the University of Manchester, Gu *et al.* (2020) developed a discrete element method-computational fluid dynamics (DEM-CFD) modeling approach for multi-track, multi-layer and multi-material SLM. They applied their simulation approach to the SLM of 316 L and Cu10Sn powders and examined the impact of energy density on the occurrence of some phenomena like balling effect, keyhole depression and lack of fusion (Figure 13). The simulation results presented in Gu *et al.* (2020) demonstrated that:

- the roughness of a previously solidified layer can lead to balling effect; and
- the energy density should constantly be adapted during the process to maintain the same melt pool profile.

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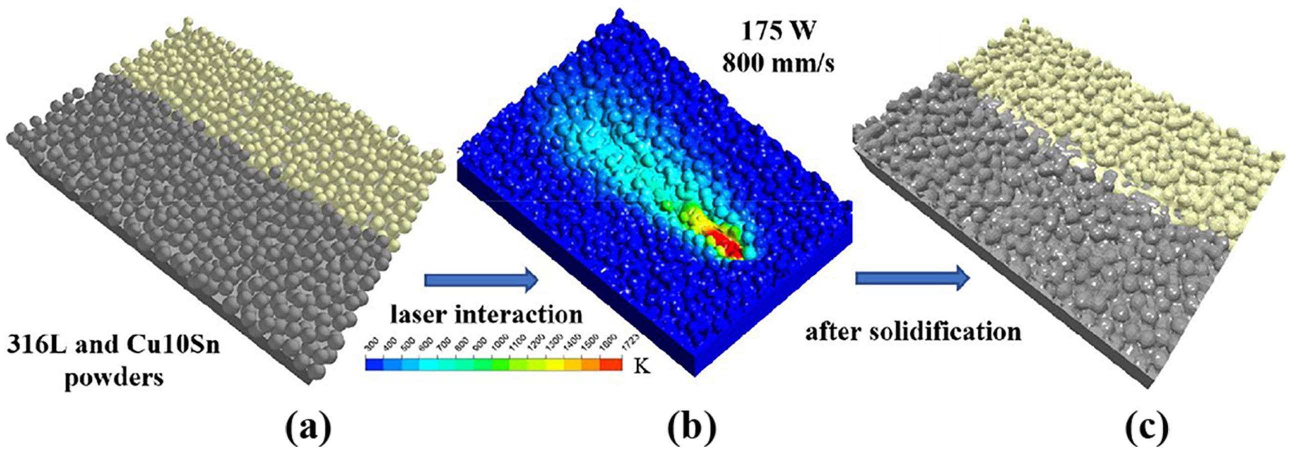
Table 2 Key information of the leading research groups in multimaterial PBF simulation

Research group	Refs.	Director	Process	Simulation method
High-value manufacturing group | Cardiff University	Gu *et al.*, 2020	Rossitza Setchi	SLM (3D)	DEM-CFD
Laser processing research center | University of Manchester	Gu *et al.*, 2020; Sun *et al.*, 2020	Lin Li	SLM (3D)	DEM-CFD
Chair of materials science and engineering for metals | University of Erlangen-Nuremberg	Küng *et al.*, 2021; Markl *et al.*, 2020; Scherr *et al.*, 2020	Carolin Körner	EBM (2D)	LBM

Figure 13 3D simulation of a multimaterial PBF process using an integrated DEM-CFD approach, reprinted from Gu *et al.* (2020): (a) initial deposition of 316 L and Cu10Sn powders; (b) a 175 W laser beam applied on the interface at the speed of 800 mm/s; (c) rack morphology after solidification



Using the same methodology as in Gu *et al.* (2020) but for different materials, Sun *et al.* (2020) took IN718/Cu10Sn powder beds in six variants and investigated the effects of these variable configurations on the melt pool dynamics and solidified track morphology. They observed an inhomogeneous temperature distribution throughout the SLMed track because of the different thermal-physical properties of dissimilar materials (i.e. IN718 and Cu10Sn). Furthermore, their simulation results showed that using a higher fraction of IN718 in the mixed powder bed leads to a melt pool with a higher temperature – a valuable conclusion that is notoriously difficult (if possible at all!) to obtain without numerical simulation. Figure 14 gives a graphical summary of the single-track SLM results of Sun *et al.* (2020), reprinted from the original reference with some minor adjustments. Despite the maturity and usefulness of the multimaterial simulation results produced by these two groups, they are not fully applicable to *in situ* alloying of a wide range of metals during PBF. This limitation is rooted in the absence of a representation of a complete material's phase diagram.

Addressing the previous *in situ* alloying issue, Küng *et al.* (2021) and Markl *et al.* (2020) recently presented an in-house simulation program called SAMPLE2D to gain a better understanding in terms of consolidation and liquid phase mixing during EBM processes (see the left diagram of Figure 15). Their offered improvement originates from the stochastic influence of the powder bed and the interplay of different physical phenomena like beam absorption, phase changes, fluid dynamics and heat conduction. The authors also conducted a simulation to explore the two-dimensional (2D) concentration distribution after an EBM process, as shown in Figure 15. These simulations, plus the results published in Küng *et al.* (2021) from the same research group, contain a process including ten layers with two different arbitrary pure metal powders and with various melting temperatures between 1,200 K (pure A) and 1,800 (pure B). Two impressive aspects of the group's work on multi-material PBF simulation are:

1 *in situ* alloying of elemental powders during PBF; and
2 Multilayer powder simulations.

However, it is necessary to address the following drawbacks in their modeling approach before applying it to more complex scenarios:

- All simulations are carried out in 2D, which is a significant limitation.
- Some crucial phenomena such as evaporation and Marangoni effects are neglected. These considerations play a significant role in shaping the melt pool flow, which is essential for understanding the process and predicting possible defects.

In recent years, efforts have also been made to investigate the capabilities of other numerical methods in modeling PBF

Figure 14 3D DEM-CFD simulation of a multimaterial PBF process, reprinted from Sun *et al.* (2020). Powder beds of IN718/Cu10Sn in different configurations (mixed vs unmixed) are investigated. The green zoombox shows the morphology and elemental distribution in braze zone

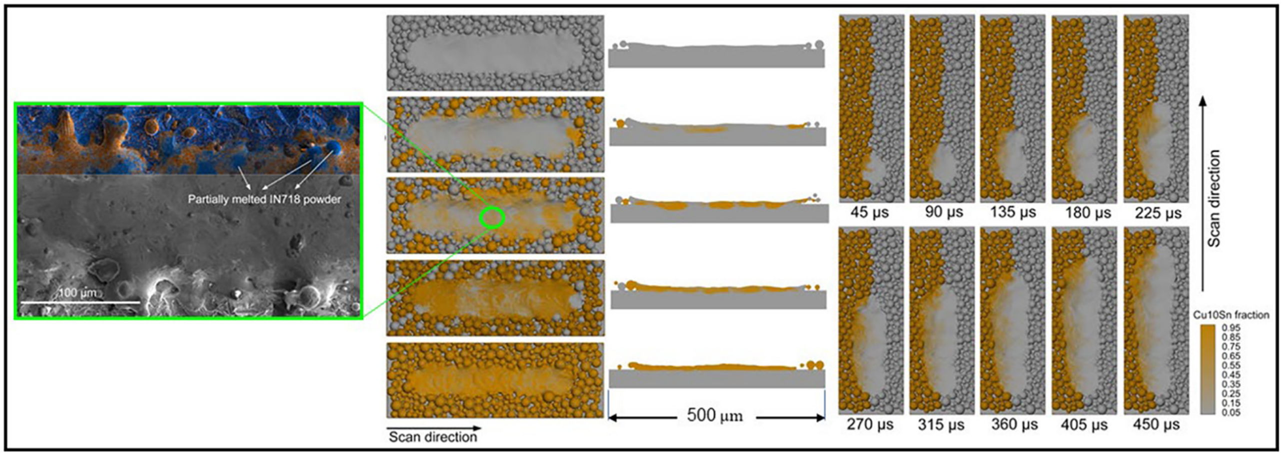
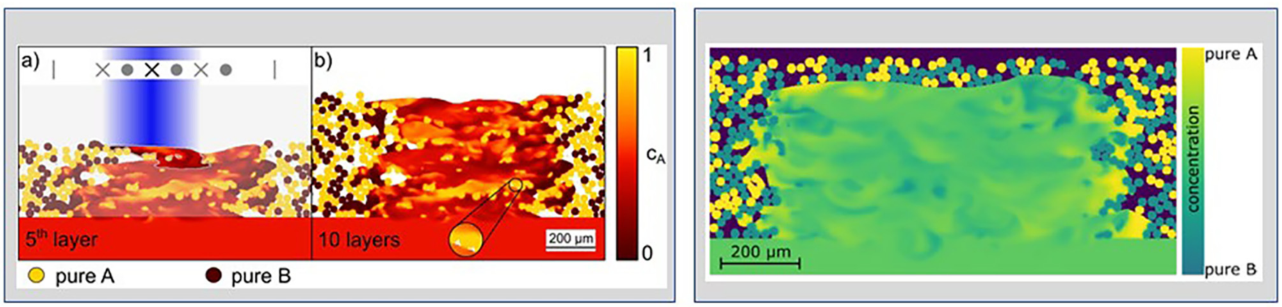


Figure 15 Left: 2D lattice Boltzmann (LB) multilayer simulation of a multimaterial PBF process using SAMPLE2D, reprinted from Scherr *et al.* (2020): (a) the electron beam acting on the fifth layer is shown in blue; (b) the final composition profile after ten layers. Right: simulation result using SAMPLE2D taken from Küng *et al.* (2021), concentration distribution after an EBM process



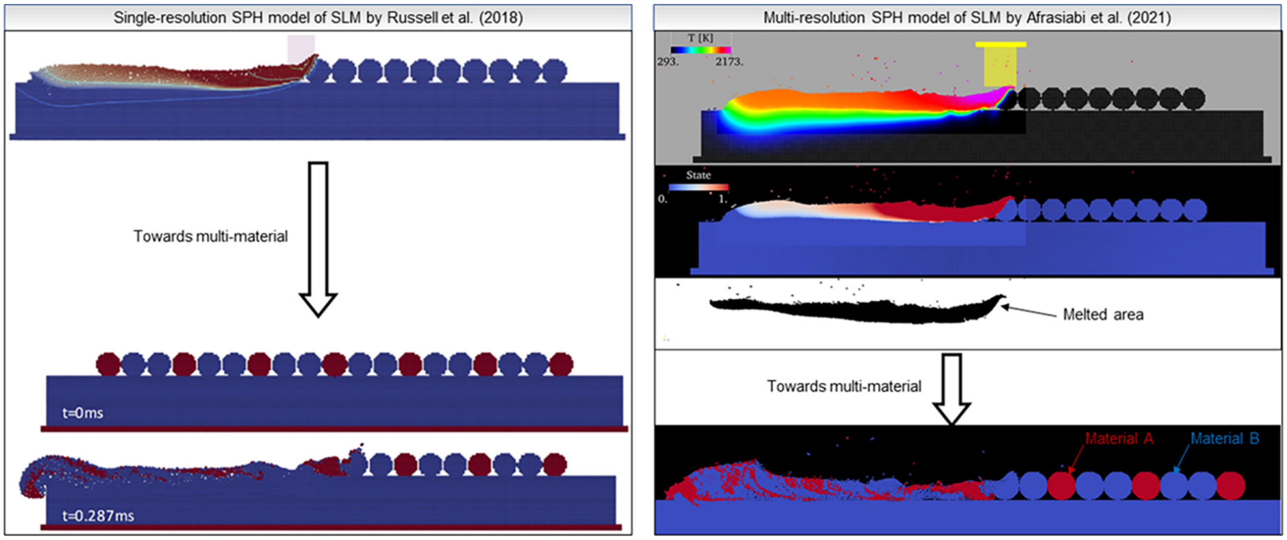
processes. Particularly worth mentioning is the adoption of (mesh-free) particle methods as a natural candidate for problems with large deformations, violent-free surface movements and extreme material transformations. The most popular of such techniques is the smoothed particle hydrodynamics (SPH) method, which has been in active use by the astrophysics and CFD community for quite some time. See in Afrasiabi *et al.* (2018b), Ye *et al.* (2019), Cleary *et al.* (2021) for further insights. While relatively new in AM, the notion of SPH in modeling laser-based manufacturing processes is not entirely unique. Examples contain the use of SPH for modeling heat transfer in the laser ablation of aluminum (Alshaer *et al.*, 2017) and an efficient thermal simulation of the laser drilling process with mesh-free schemes (Afrasiabi *et al.*, 2018a, Afrasiabi and Wegener, 2020).

To the best of the authors' knowledge, a particle-based computational model of multimaterial PBF has not been developed yet and is still missing from the literature. Nevertheless, several developments already exist in using SPH for mono-material PFB applications that reveal its potential and remarkable efficiency for multimaterial problems. Indicatively, the 2D meso-scale SPH framework of Russell *et al.* (2018) is the first of its kind in terms of showing a systematic approach for a detailed and well-resolved model of a single-track SLM process. The authors proposed a doped powder bed as a proof-of-concept to demonstrate a unique advantage of using a Lagrangian numerical method like SPH in modeling multimaterial PFB. They highlighted in their paper that SPH, contrary to the Eulerian numerical approaches used in previous studies (King *et al.*, 2015a, Khairallah *et al.*, 2016), can trivially track the motion of a specific material point at any time over the length of a simulation. Intending to speed up the simulation, Afrasiabi *et al.* (2021) introduced spatial adaptivity to the SPH framework of Russell *et al.* (2018) and achieved a significant enhancement in the computational performance of their code. A graphical summary of these results is shown in Figure 16, suggesting that the extension of particle-based PBF models from mono-material to multimaterial is straightforward and needs to be considered an immediate future work.

5. Summary and future directions

In this review, a comprehensive investigation of multimaterial PBF techniques from both experimental and numerical perspectives was carried out. First, an explanation of different

Figure 16 2D SPH simulation of a single-track SLM process, reproduced from Russell *et al.* (Russell *et al.*, 2018) and Afrasiabi *et al.* (Afrasiabi *et al.*, 2021), to demonstrate the ease of multimaterial implementation in Lagrangian numerical schemes



mono-material PBF processes with the corresponding advantages and disadvantages was given. Then, most notable studies on the use of multimaterial in SLS, SLM and EBM processes were discussed. For SLS, one of the major disadvantages is material waste occurring as unfused "support" powder. Although it is possible to reuse the unfused powder and mix it with a new powder in different ratios, the exposed polymer powders undergo chemical changes when exposed to high heat for long periods. This makes their sintering characteristics less predictable. The most significant breakthrough was from *Aerosint* that created a commercialized machine, applicable for multiple materials in a single SLS process. This system, however, requires fundamental research concerning the material properties and process parameters in multimaterial SLS technology.

In the field of multimaterial SLM, more remarkable progress has been made involving a larger body of research. Many published articles could be found on the topic of multimaterial SLM. Consequently, progress is faster and more significant as multiple research papers show their own built or modified multimaterial SLM machines. A suggestion in this regard is to improve the verification and validation of the experimental insights by numerical simulations. Future developments in these fields would continue to advance the technologies to the point where they can be turned into industrial products. Therefore, investigating the relationship between material properties and process parameters, as well as the impact of different material properties on a single building process, would be a valuable opportunity for future research. To be able to identify defects automatically, the examination of individual layers and the identification of defects also needs to be studied.

There exist few works with a limited number of materials for the EBM multimaterial process. Similar to the SLS process, this technique still has many opportunities and undiscovered issues related to the material and process parameters. Recent PBF modeling efforts can speed up the fabrication process and discover new materials and methods. No relevant studies on the multimaterial MJF process were found in the literature. The main reasons for that lie in the newness of the technology and a limited range of investigated materials. Thus, conducting experiments with different available materials are recommended, supported and validated by HP, using the available fusing and detailing agents. The future of multimaterial 3D printing seems to be heavily dependent on its dedicated research studies and more industrial partnerships.

Numerical simulation of multimaterial PBF processes is still in its infancy stage, as evidenced by a very limited number of available published works. In such applications, new challenges and research questions to address are mainly rooted in the co-existence of different materials with different metallurgical and thermophysical properties. Reliable computational models of multimaterial PBF rely on a multiscale analysis, requiring a coupled approach (i.e., solid mechanics, fluid mechanics and thermodynamics) to capture a wide range of complex phenomena such as phase formations, material intermixing and residual stresses. Existing 3D simulations of multimaterial SLM use a combined DEM-CFD approach and demonstrate impressive results; however, their simulated geometry is still far from a lab-scale experiment (less than 0.5 mm track length with only one powder layer). It appears that the high cost of computation and numerical stability issues associated with powder-scale simulation are significantly intensified in multimaterial PBF problems, where intricate melting/solidification and multiple material interfaces are involved.

A potentially more efficient approach than grid-based or kinetic (e.g., LBM) techniques for this application is using Lagrangian particle methods. These methods offer a unique strength in handling violent free-surfaces and multiple material transformations – some challenging issues that are far too difficult to resolve within grid-based numerical frameworks in multimaterial situations. Another area where additional effort is required would hinge on rigorous model validation, in which conducting a series of *in situ* experimental measurements for material parameters is inevitable. With the recent development of particle methods and computing hardware, a fast particle-based code with *in situ* identification of material parameters appears to be the most sensible route forward in modeling multimaterial PBF processes.

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Corresponding author

Mehrshad Mehrpouya can be contacted at: m.mehrpouya@utwente.nl