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Additive manufacturing of metal components – process-material interaction in different process chains.

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Abstract. In this paper we describe metal additive manufacturing (AM) processes in general, and laser bed fusion processes in particular. The process characteristics are described, and the various modelling approaches demonstrated. The open AM architecture developed at DTU Mechanical Engineering is introduced, as well as an alternative process chain based on AM and subsequent injection moulding.

1. Introduction
Additive manufacturing (AM) [1,2], is a hyponym that covers a family of technologies that conversationally is known as 3D printing. AM is regarded as a digitally born family of processes, that embodies the digital and physical aspects of layered manufacturing into a cyber-physical unit, thus nourishing by its nature a wider trend, namely the digitization and automation of the manufacturing industry [3,4]. For this reason, the increasing adoption of AM within the manufacturing industry is pushing companies to research new ways of adapting and optimizing their manufacturing strategies by integrating these digital technologies of tomorrow into existing production, and by bolstering their strategies towards a physical to digital conversion.

To illustrate the link between the physical and digital process of AM, figure 1 serves as an overview of the gross elements for a generic AM process. All elements pertaining to the physical and digital process chain are listed in white slanted boxes.

The subdivision of technologies within AM that pertains to metal is provided in figure 2 below. Figure 2 offers an overview of which technologies exist for the additive manufacture of metal components, abstracted in terms of the state of fusion, feedstock condition, and how the feedstock is distributed and fused to solid matter. Additionally the technologies are named according to their generic names as indicated by the ASTM/ISO 52900:2015 standard [1].

Process 1 – A filament arc welding process by which a metal wire is fed through a nozzle that also serves as the anode in the weld circuit. The wire is advanced under the cover of an inert gas towards the work-piece, which is the cathode of the circuit. As the wire is advanced, a plasma arc is formed between the anode and cathode, melting and depositing the wire onto the work-piece. This process has in recent years seen adaption for niche big-area additive manufacturing applications.
Figure 1. Overview of the physical and digital links of an AM process chain [5].

Process 2 – A cladding processes by which a metal powder is fluidised and jetted onto the work-piece while being intersected by a laser beam to melt the powder to a liquefied spray. As the high-velocity spray hits the work-piece the droplets adhere to the surface forming a thin layer. This process is known as cladding and seen in niches metal additive manufacturing where wear/resistant coatings are sprayed onto the work-piece as a finishing procedure or in hybrid manufacturing where each added layer is subsequently machined.

Process 3 – A powder-bed process where a thin layer of metal powder is coated over the work-piece in a confined build-chamber, known as a powder-bed. After deposition of a layer, the layer is consolidated by means of a high powered electron-beam emitted under vacuum by a magnetic field deflected electron beam gun. This process is renowned for allowing for high-speed beam modulation as no mechanical subsystems are involved in deflecting the electron beam and for allowing for high build-chamber temperatures, whereas the process is limited by the availability of process materials and from cumbersome maintenance of a high vacuum process environment.

Process 4 – Laser induced powder-bed fusion. Very similar to the e-beam technology, this process relies on a high-powered laser for melting of the powder. and has therefore been highlighted in the matrix. The process will be described in detail in the following sections.

Process 5 – A variation of Process 4, employing slightly less laser power while fusing the powder. Through this process the individual powder grains are now fully melted through the formation of a melt-pool. The powder is heated to some 10-20 degrees below its melting point allowing for the powder to become sticky such that the selectively heated grains stick and adhere to neighbouring grains. This will form a considerably weaker but porous metal structure that is often sought for metal components for medical implants. The porous structure allows the implants to form a mechanical inter-lock with organic tissue inside the human body, thereby to a certain extent eliminating the need for implant screws and adhesives.
Process 6 – The final process in figure 2 is the only process by which a work-piece is built from metal sheets. This process involves cutting thin metal sheets to contour by means of a high-powered laser or by a punch. Subsequently the sheets are stacked and welded by use of ultrasonic welding to form the component. This process is at the time of writing rarely used in industry, but is included here for legacy purposes.

Figure 2. The realm of metal based AM processes, and their characteristics [5].

2. Basic process steps of powder bed fusion (PBF)

The metal powder bed fusion (PBF) process can be construed to have five major aspects which have considerable impact on the overall process:
1) Powder delivery and powder bed formation
2) Generation and delivery of energy source
3) Energy-material interaction
4) Local material consolidation
5) Global thermal processing

The basic process chain, however, follows up the PBF with an equally important heat treatment post-process aimed at relieving stresses and/or controlling the microstructure. Each of these five steps are described in greater details in subsequent sections.

2.1. Powder delivery and powder bed formation

The metal powder bed fusion process, as the name indicates, begins with the formation of the powder bed. A powder delivery system e.g. a hopper, deposits a heap of fine powder particles over the build-plate, which is then spread using the sweeping motion of a recoater blade (or a roller or scrapper). The system is also responsible for relocating the build plate along the vertical-direction, and therefore defines the accuracy and resolution of the build in the vertical direction. This relocation of the build plate creates a small gap between the tip of the recoater blade and the build plate to allow the deposition of the
required powder layer. At subsequent recurring stages of the PBF process, the powder is spread on top of the previously manufactured layers and thus the interaction of the recoater blade with the surface of the previous layer becomes significant as well. See figure 3.

![Figure 3. Schematic 3D view of a typical laser-PBF machine along with the components [6].](image)

### 2.2. Generation and delivery of energy source

The typical energy source used in the case of metal PBF is either a focused laser beam or an electron beam with high energy density. The laser is essentially light (i.e. electromagnetic waves), created by a phenomenon denoted stimulated emission, with high spatial and temporal coherence properties, which allow it to be focused in a very small spot and achieve a narrow spectrum, respectively. The generated laser beam is passed through several lenses that regulate the optical characteristics of the beam, and is then made incident on a mirror that controls the incident location of the laser beam on the powder bed. Following the wave-particle duality of light, the interaction of the laser beam with the lenses and the mirrors can typically be described by the concepts of ray optics while effects such as absorption of the laser beam in the optical elements (mirrors and lenses), polarization, or thermal lensing, invoke the electromagnetic wave characteristics of the laser. During the additive manufacturing process, the laser beam is selectively manoeuvred across the powder layer to consolidate the metal powder particles and to create the desired geometry.

### 2.3. Energy-material interaction

The core of the metal AM process begins when the laser beam (or electron beam) is incident upon the powder bed. In broad terms, a portion of the laser beam is directly reflected away, a second portion undergoes scattering, a third portion is absorbed by the powder/bulk material and a fourth portion is reflected into the powder bed and undergoes multiple cycles of reflection, absorption & scattering. The overall absorption of the laser beam depends upon the wave characteristics of the laser (wavelength, monochromaticity, etc.), the properties of the material (albedo, refractive index, emissivity, etc.) as well as the characteristics of the powder bed (powder packing, powder morphology, powder composition, etc.). The actual laser-material interaction is often quite complex and can only accurately be defined through the radiative transfer equations.

### 2.4. Local material consolidation

The energy-material interaction can lead to two distinct types of material consolidation, namely sintering and melting/fusion.

#### 2.4.1. Sintering:

Sintering bonds powder particles at their interface through diffusion mechanisms, as shown in figure 4, and thus forms a solid (porous) structure through heating without complete melting.
Neck growth occurs between formerly separate metal particles followed by shrinkage of the particles into a solid [7]. The bonded bulk material exhibits different global properties (such as strength, density, ductility, and thermal/electrical conductivity) as compared to the powder bed. The nature of the sintering process makes it prone to the formation of pores medially between the surrounding particles. Material consolidation through sintering always occurs in a PBF process.

![Diagram of solid state sintering](image)

**Figure 4.** The principle of solid state sintering.

**2.4.2. Melting/fusion:** In regions with sufficiently high energy density, the consolidation of the powder particles can instead proceed by complete melting as shown in figure 5. The rapid melting and solidification enabled by the process, allows for parts with tailored properties, distinct from those obtained from traditionally processed parts [8]. This facilitates the exploitation of localized material properties, obtained from refined microstructures, formation of non-equilibrium phases, and supersaturated solutions. This mode of material consolidation is more sensitive to process instabilities, potentially leading to formation of melt spatters, localized secondary-phase particles (such as oxide and carbide inclusions) or extremely fine refined microstructures.

![Diagram of full melting/fusion](image)

**Figure 5.** The principle of full melting/fusion of a workpiece.

**2.5. Global thermal processing**

Neglecting the small region with the melt-pool (and/or being sintered), the metal AM process globally resembles a non-homogenous non-isothermal heat treatment processes. This in-situ heat treatment can generate considerable transient thermal stresses, initiate local plastic yielding and hardening, and finally cause large residual stresses within the part. Furthermore, the rapid cyclic thermal conditions result in non-equilibrium microstructures with varied mechanical properties (as compared to the powder material). Thus, as mentioned earlier, a typical PBF process chain always involves a secondary heat treatment and/or stress relief post-process.

Following the PBF process, several post-processes can also typically be required before a functional part within dimensional and surface tolerances is achieved, e.g. multiple heat/solution treatments, machining, grinding, and polishing. A removal process of the part from the build plate must also be carried out by, e.g., EDM (electro-discharge machining) or band-sawing, and support structures (if present) must also be removed during the post-processing stages. A post-process step of hot-isostatic pressing is also common in parts produced with densities below 99% (compared to bulk material).

**3. Modelling of metal AM**
The PBF process chain results in a large set of significant control parameters. Consequently, determining stable and optimum process windows is an arduous activity for metal PBF. Empirical models relating the most common parameters (e.g. power and scan speed) with typical properties (tensile strength, fatigue life, etc.) are difficult to obtain, and instead the current research across the literature aims to identify process signatures that can indicate resultant properties and defects.

In metal AM (including PBF), the distinct process signatures and defects arise due to various phenomena occurring across several length and time scales. From the process viewpoint, the smallest length scale typically corresponds to the wavelength of the laser beam being used (e.g. 1.06 µm for a Nd YAG laser system). However, from a material science perspective, even smaller features such as nano-precipitates and micro-/nano-porosities become relevant for the metal AM process, thus making nanometer length scales significant. On the other hand, warpage effects (i.e. localized distortion/bending) on metal AM components only become practically relevant in parts which are several centimeters large (in each dimension). Thus, the range of relevant length scales for metal AM can vary from the nanometer (10⁻⁹ m) to centimeter (10⁻² m) scale, corresponding to at least seven orders of magnitude. Similarly the relevant time scales for the process can vary from microseconds (time for the laser beam to pass over a powder particle) to several hours (time for a complete build), corresponding to 10⁻¹¹ orders of magnitude.

Consequently, a goal-oriented approach (typically motivated by the type of process defect/signature of interest) of grouping the various phenomena into broader categories of micro-, meso- and macro-scale is followed, wherein the multiphysics involved at the relevant length and time scales are handled with greater accuracy, while the contributions from phenomena occurring at larger or smaller scales are typically approximated.

3.1. Empirical models

As mentioned earlier empirical models for additive manufacturing are difficult to generate due to the extensive set of significant parameters and the corresponding volume of experiments that would be required. However, the ease of application of empirical models during decision-making (e.g., during the design and/or process planning phases) has nonetheless promoted experimental campaigns aimed at such model development. As a case in point, simple prediction models for predicting the expected roughness at a specific location within a channel produced by AM are being generated that can be used during the component design phase – with a potential application in conformal channel design.

The benefits of conformal cooling channels over conventional cooling channels have been known for some time [9], with the performance of such channels known to be determined by the actual geometry of the channel, the cross-sectional area and the internal surface texture. However, build features of PBF components have been shown to be dependent on the angle of the component with respect to the build plate, and the roughness on the surface has been found to increase with decreasing inclination angle [10-11]. Investigations further indicate that the roughness of PBF channels are dependent on two orientations, namely the global orientation (α) and the local orientation (β). The investigated components are shown in figure 6 and the definitions of global and local orientations may also be seen in figure 6.

The test samples seen in figure 6 were manufactured using the laser PBF process in a 17-4PH stainless steel. The analysis of these test samples was conducted by X-ray CT (computed tomography) scanning seven channels with an equal diameter of two millimeters in seven different global orientations: 0°, 15°, 30°, 45°, 60°, 75° and 90°. The roughness of the channels was analyzed using an in-house Python image analysis code. The results of the Python code analysis are visualized in figure 7 and can be summarized as: “the larger the α angle, the smaller the induced roughness”. More quantitatively, the surface roughness follows a Student’s t-distribution with respect to the α angle – thus enabling development of an empirical model relating design feature characteristics with surface roughness.
Figure 6. Left: Investigated test samples. Right: Definition of the global build orientation $\alpha$.

Figure 7. Through view of the channels, visualizing the roughness dependence on the location inside a channel (local orientation $\beta$) and build direction (global orientation $\alpha$).

3.2. Meso-scale model
Meso-scale models of the PBF process are focused on simulating the powder bed formation, the laser-material interaction and the local material consolidation aspects. Powder bed formation is typically modelled using either the Raindrop packing algorithms (which randomly deposit powder particles) or using DEM (discrete element method), which also considers interaction forces among powder particles and from the roller/scrapper/blade. Models for laser-material interaction at this scale range from complex ray-tracing methods tracking specular reflection, to computationally-intensive radiative transfer equations that consider diffuse reflection and wave optical characteristics of the laser. The local material consolidation is also simulated with similar high fidelity by involving thermo-fluid dynamic models that can consider temperature-dependent material properties, solid-liquid-vapor phase changes, surface tension gradient driven Marangoni effects and thermo-capillary effects of the powder bed. Figure 8 shows a simulation of a single track formed during PBF through such a complex meso-scale model involving DEM for powder bed formation, ray tracing algorithms for laser material interactions, and the above mentioned thermo-fluid model [6]. Through such modelling, it is possible to predict the irregularity and stability of the individual tracks, the formation and evolution of porosities, and the resultant metrological characteristics of the surface. The simulated domains, however, are small in size due to the large computational requirements.
3.3. Micro-scale model

Micro-scale models of the PBF process have a focus on simulating the laser-material interaction, the local material consolidation and the global thermal processing aspects. The typical goal of these models is to determine the thermal (and mechanical) conditions and therefrom predict the emergent metallurgical and material properties. The geometric and optical/electromagnetic complexities of meso-scale models are often not of primary interest here and hence the powder bed is typically modelled using either an equivalent porous continuum assumption or using the Raindrop algorithms. Similarly, laser-material interaction models range from simplified assumptions of surface fluxes/volumetric sources calculated through empirical models, to ray-tracing methods tracking specular reflection. The local material consolidation can be simulated with a similar high fidelity as for meso-scale models, but use of simpler equivalent conductivity-based thermal models is also common. The micro-scale simulations also include models to predict the metallurgical microstructure, either directly through cellular automata or phase field techniques, or indirectly through the use of empirical models for phase fraction predictions. Figure 9 shows temperature results from such an implementation for simulating PBF of two different tensile bars of Ti6Al4V [12]. The difference in the thermal history pattern at different locations and due to orientation resulted in different microstructures (phase composition as well as morphology) at the middle and bottom parts of the samples.

Figure 10 shows the microstructure predicted during a parametric study of laser scan speed and laser beam size. The solid red and black lines show the borders of the region corresponding to equiaxed and columnar grain formation, while the individual dots correspond to different (fixed) locations at which the solidification and thermal parameters are calculated. The figure displays the relative abundance of columnar grains in the domain for all investigated parameters – corresponding to the typical experimental observation for metal PBF. Thus, through such modelling, it is possible to predict the local microstructure and mechanical properties of a part produced by PBF. The size of the simulated domains for micro-scale models is typically correlated to the computational requirements of the chosen metallurgical models.
Figure 9. Thermal history modelling results. a) Bottom and b) center of a horizontal tensile bar specimen. Vertical tensile bar specimen: c) bottom and d) center. [12]

Figure 10. Thermal gradient-vs-growth velocity maps extracted at melt pool boundaries during single track PBF simulations by varying (a) scan speed and (b) beam size [13].
3.4. Macro-scale model

Macro-scale models of the PBF process are focused on simulating the global thermal processing aspect. Powder bed formation at this scale is typically modelled using an equivalent porous continuum assumption. Laser-material interaction models apply equivalent volumetric sources calculated through either empirical models or analytical solutions based on simplified assumptions. The local material consolidation is typically simulated through simpler equivalent conductivity-based thermal models. At this scale, the thermo-mechanical effects become significant and so prediction of residual stresses and distortions are among the primary goals. Constitutive models for elasticity, plasticity and visco-plasticity are used along with models for thermal-softening and work-hardening to predict both the local material properties, and the resultant behavior of parts produced by PBF under the large thermal (stress) loads. Figure 11 shows a macro-scale thermo-mechanical model implementation where two cantilevers have been produced using PBF. The cantilever corresponding to the top of the image is then detached from the build plate (leading to a certain warpage). Subsequently, both cantilevers are subjected to the same stress-relief and heat treatment cycle, and then the second cantilever is also detached from the build plate. The figure clearly shows the much larger warpage in the component detached prior to stress relief as compared to the cantilever detached at the end. Through such modelling, it is possible to predict the warpage, residual stresses, and stress-driven delamination, as well as the fatigue/damage behaviour. The size of simulated domains in such models are typically in the order of centimetres i.e. at the scale of the parts.

![Figure 11. Different distortions observed in two identical cantilevers produced by PBF subjected to different sequences of the same chosen post-process steps.](image)

4. Open metal AM architectures

Although academic research within the field is growing exponentially, with 2000 publications in 2010 and 10000 publications in 2018, the vast majority of these publications are on research peripherally related to AM, such as design for AM, applications of AM, simulations of AM processes, characterization of input and output material, and post-manufacturing quality assurance. Research that pertains directly to the principle of operation of the AM system to improve the capabilities of the process is virtually non-existent in said statistics. This is due to the complexity of the principle of operation of AM processes as shown in figure 1, and, to a large extent, due to the very closed and proprietary nature
of industrial AM systems. It is necessary therefore to institute a liberation of this restricted area of
development by stringent advocacy and practice of open research on the philosophy of open
architectures and open source platforms, so that academia may assist in driving research in AM beyond
the current state of art. By this philosophy, the Technical University of Denmark has developed and is
continuously improving on, two metal laser powder bed systems that challenge the established industrial
standard by introducing capabilities such multiple powder hoppers for multi-material manufacturing, as
well as a fully open laser and galvanometer modulation system that allows for high speed laser pulse
shaping and an open hardware melt pool monitoring system that is currently under development.

4.1. Multi-material capable Laser PBF system
Since Laser PBF involves continuous laser welding in a small cubic volume, it presents a unique
materials challenge. Suitable material alloys need to be able to withstand very high cooling rates while
simultaneously retaining a good microstructure and low distortion from residual stress. Hence, many of
the alloys developed for casting and welding are not exactly ideal for laser PBF. However, due to the
wide availability of these alloys they are predominantly used with some degree of success. Working
with open-architecture AM systems enables tailored materials development at a significantly faster pace.
So far, directed energy deposition processes (DED) are mainly associated with multi-material additive
manufacturing in metals, due to their intrinsic system-related flexibility of changing to different
feedstock during operation. However, PBF based additive manufacturing processes exhibit specific
advantages over DED, such as the possibility to generate more intricate geometries and to achieve
smaller feature sizes. At the same time, most commercially available PBF systems are limited to a single
powder feedstock restricting the deployment of different materials during the build process. Aurora Labs
S-titanium pro system utilizes a unique powder hopper delivery system as shown in figure 12. The open
architecture allows for a precise layer-by-layer compositional control by mixing up to three different
powders. The power source is a set of two 150 W CO2-lasers fired simultaneously. The two beams pass
separately through a set of optics before entering into the focus lens resulting in a single spot of approx.
150 µm in diameter in the processing plane. Thereby, the focus lens is mounted onto a moving print
head in an X-Y gantry system. The average maximum power output of the focused beam is 255 W at
the processing plane. In the Aurora labs system, we successfully made discrete and continuously
changing interfaces between stainless steel (SS 316L) and maraging steel (MS1). The etched
microstructure in figure 12 shows the ability to gradually transition from one material to the other.
Vickers micro hardness and elemental maps showed a smooth as designed transition, without stress
concentrations [14]. The ability to make functionally graded multi-material components provides an
expanded materials design paradigm

4.2. Fully customizable open-architecture laser PBF system
The main constituents of the Technical University of Denmark (DTU) open architecture laser PBF
system are the laser scanning module, the powder-bed, the recoater/scaper, and the control system of
the machine. The optical module is comprised of a 250W laser, SPI-250C, that can be modulated at
100kHz, and, a galvanometer system (Thorlabs GVS012). The powder-bed and recoater module have
been tailored towards research purposes [15]. The hardware modularity allows for experiments
comparing scan strategies, feedstock and in-situ sensor integration. It also allows the study and causality
of every physical component within the system on part quality, thus enabling an iterative and quick
redesign capability.

This section presents the chosen approach to gain full control over the process flow in laser PBF.
The control system enveloping the open architecture platform includes a laser modulation and
galvanometer unit that can allow for high-speed modulation of both the beam trajectory and laser output
power [15]. The control system is comprised of a hardware controller, its embedded firmware and an
interface to a host-side job-planner, all of which have been tailored to experimental powder-bed fusion,
allowing the research scientist to freely explore scan strategy, pulse modulation, speed, laser power, and
beam shaping. The system will also be capable of cross-talk to industrial PLCs and controllers for NC stages, such that the powder-handling system allows for complete low-level hardware control.

Powder-bed fusion relies heavily on automation throughout the entire process flow. This starts with an approximation of the computer model into a triangularly tessellated surface, described by vertices and direction. Next, the tessellated surface approximation is interpreted through a job planner. Aside from geometrical interpretation, the job planner is also responsible for introducing the process parameters applied throughout the build. Thus, a custom and fully open job planner has been developed to take a 3D geometry and process it into a layer-wise pattern, then to convert it into a job-file that can be processed by the laser and galvanometer controller unit. To increase usability of the planner a graphical user interface allows adjustment of process parameters such as hatch line spacing, laser-power, and scan speed amongst others.

The laser and galvanometer controller unit has been designed such that it receives angular mirror positions and laser modulation parameters from a host computer over a high-speed USB interface and from this generates the appropriate control signals to the interfaces available on the laser and galvanometer subsystems. Most industrial fibre lasers can be modulated from an analogue 10V control signal, and most analogue galvanometers can be interfaced with an analogue ±10 V control signal. At the heart of the Galvanometer Laser and Modulation System, a high performance 32-bit ARM® Atmel SAM3X8E Cortex® microcontroller is implemented. In addition to the on-board capabilities, 16 bit digital-to-analogue converter and operational amplifiers have been implemented in order to achieve the necessary interfacing capabilities. In addition to the interfacing enabled by the modulation and control unit, the Atmel SAM3X8E Cortex® allows interfacing to an additional 47 digital I/O streams and 12 analogue inputs.

5. **Alternative process chain using AM for making metal components**

Powder injection molding (PIM) is a well-established process that allows mass production of metal and ceramic components with fairly complex geometries [16]. Depending on the complexity of the produced parts and materials choice, the process usually become more economical above 1000 to 10000 parts. The high cost of the production of the molds makes this technology non-remunerative for low rate manufacturing. Moreover, another constraint of this process is the need for a two plate mold, to allow...
removal of the manufactured piece after injection moulding. This generates a certain degree of restriction when complex pieces have to be produced. A common problem for injection molding parts, for example, is the one caused by the undercuts. Due to these problems, when highly customized parts are needed, or in the case of prototyping and pilot production, machining or additive manufacturing has to be chosen instead of PIM [17].

The process so-called “3D-Printing Integrated Manufacturing System (3DIMS)” is under investigation as an innovative process for powder injection molding, making possible the use of this technology particularly when low-volume production and high geometrical complexity of the part are required. In this process, AM is used to fabricate a sacrificial mold for the use in PIM. The process chain is illustrated in figure 13. The introduction of AM in the process chain leads to necessary adjustments in the feedstock for PIM, as well as in the process parameters. The mold is fabricated by a photocurable polymer (or photopolymer) using a DLP (Direct Light Processing) or SLA (stereolithography) process. In this process, hardening of the liquid resin occurs as a result of cross-linking of the polymer when it is exposed to UV (ultraviolet) light. The strength of the material is sufficient to withstand a certain level of injection pressure. The mold has a cavity with the desired geometry. However, the printed part is often only part of a mold, the so called “insert”, instead of an entire mold plate. The design of the AM parts and its material properties are crucial for the success of the process. Most of the commercially available photopolymers are rather durable with regard to exposure to all kinds of chemicals. In 3DIMS, a special grade of photopolymer is used. After UV curing, the resin is able to be dissolved in aqueous solution.

The printed mold insert (after cleaning and a series of post processing steps) is mounted in an injection molding machine. The feedstock which contains metal power is injected into the mold by a screw or a piston. Typically the metal content is more than 60% in order to assure the strength during debinding and sintering. A modified Polyethylene-Paraffin Wax binder system can be used in the feedstock. The green body forms inside the mold. Compared with a conventional mold that is made in metal, the strength of photopolymer resin can be up to four orders of magnitude lower than steel. The chosen binding system must lead to feedstock with low viscosity during injection molding in order to reduce injection pressure as much as possible. At the same time, the geometry must be well maintained during all other steps (demolding, debinding and sintering).

In the ejection step of injection molding, the printed mold is ejected with the green body inside. This means that the actual demolding is executed outside the injection molding machine in an additional step. The mold should be removed by dissolution in an aqueous solution. Due to the non-water-soluble binding system in the feedstock, the geometry of the cavity will be well replicated by the feedstock material and not damaged during the dissolution process. The green body is then debinded and sintered in a furnace in a protective atmosphere. The selection of binder system and a suitable debinding procedure is believed to play a key role in the entire process chain. Nowadays there are different lost-forming technologies for PIM. For example Hein et al. [18] proposed a process chain with a sacrificial mold for PIM, where in this process the DLP printed mold is removed by thermal degradation after PIM. Similar to 3DIMS, the general feasibility could be demonstrated, but further optimization of the process is required before it can be transferred to industrial production.

![Figure 13. Process chain of the 3D-Printing Integrated Manufacturing System.](image-url)
6. Summary
In this paper we have discussed a classification of AM processes and more specifically described metal AM processes. Details of the PBF process have been described, alongside with the various aspects of modelling. The approach of an open AM platform has been introduced as a key enabler for process development and optimization. Finally, an alternative process chain for realizing metal parts based on AM has been introduced.

Certification and qualification of AM components is the primary driver necessary for wide-scale implementation of metal AM technologies in industry. The components that are typically suited for metal AM also require high geometrical and mechanical performance tolerances. In a dynamic process such as PBF, there are hundreds of process variables that could affect part quality and performance. Hence, the best certification methodologies use in-situ sensors to gather process data that are otherwise unavailable ex-situ. The open AM architecture philosophy at the authors’ university helps us work in synergy with process data and multi-physics models to ensure that realistic and industrially applicable quality management (QM) techniques are developed for AM processes and component certification.

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