Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

POTENTIALS AND CHALLENGES OF MULTI-MATERIAL PROCESSING BY LASER-BASED POWDER BED FUSION

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Abstract

Multi-material additive manufacturing offers a multitude of opportunities for increasing functional integration beyond the current state of the art. However, the real potential is only vaguely described and there are also challenges alongside the new opportunities. This paper presents a systematic collection of the challenges to be overcome by laser-based powder bed fusion before it can provide industrially relevant multi-material processes. Amongst others, parameter adaptation to avoid micro-cracking, relevant process monitoring technologies (e.g., thermography-based layer monitoring) and potential approaches for powder separation (e.g., using ferromagnetism) are described. Furthermore, to exploit the full potential of multi-material designs, possible concepts for the integration of fully functioning mechatronic devices into multi-material parts are also presented.

Introduction

Additive manufacturing (AM) has a lot of potential for the production of complex structures because it utilizes layer-based fabrication. One of the most widespread technologies for the production of parts from metals is laser-based powder bed fusion (LPBF), a powder-based system that uses a laser for solidification [1]. However, this concept is limited to the production of parts made of just one material. The reason for this limitation is the powder coating system. Generally, a scraper blade or roller is used to allocate the powder in a homogenous layer throughout the build chamber [2].

The implementation of a multi-material concept affects the entire AM process chain. New challenges arise during data preparation; the processing of the different materials requires different monitoring tools and the integration of electronic systems while the recycling of the multi-material powder mixtures introduces a new set of problems. Nevertheless, multi-material AM can still be divided into the same three stages as mono-material production (pre-, in- and post-process).

This paper presents the latest progress in the overall process chain of multi-material machining. Firstly, this study introduces the general multi-material laser-based powder bed fusion process chain. Secondly, a typical multi-material application is presented and the data preparation is described for the pre-process using this example. Thirdly, results regarding the thermographic detection of defects in multi-material powder layers are presented. Furthermore, a procedure for the locating of sensors and actuators in LPBF components is introduced and verified as part of a case study. Lastly, the occurring metal powder mixtures are characterized in terms of their mixing ratios and material properties to identify relevant recycling strategies.

LPBF based multi-material processing

Following the guideline VDI 3405 [3], the AM process chain can be separated into pre-, in- and post-process. Figure 1 illustrates this structure for laser-based powder bed fusion and its adaption for multi-material applications.

During the pre-process, build data is prepared. Accordingly, a surface model (STL file format) derived from the volume model by triangulation is sliced into layers of a defined thickness (layer model). Process parameters, such as laser power and scan speed are assigned to it. After data preparation, the actual part building takes place during the in-process. A detailed description to the steps of the multi-material process can be found in [4]. A further advancement of the building process is process monitoring using e.g. optical systems to provide quality control of the manufactured parts, to improve understanding of the process and to simplify further process parameter definition. Another development is the automated integration of sensors and actuators during the build process in order to create mechatronic parts. A first idea of how a machine must be modified and how such an enhanced process might look like can be found in [5]. The following post-process can be divided into thermal and mechanical treatments of the part, and powder recycling [6].

Results and approaches in the pre-, in- and post-processing areas of multi-material laser-based powder bed fusion are presented in the following main section of this paper.

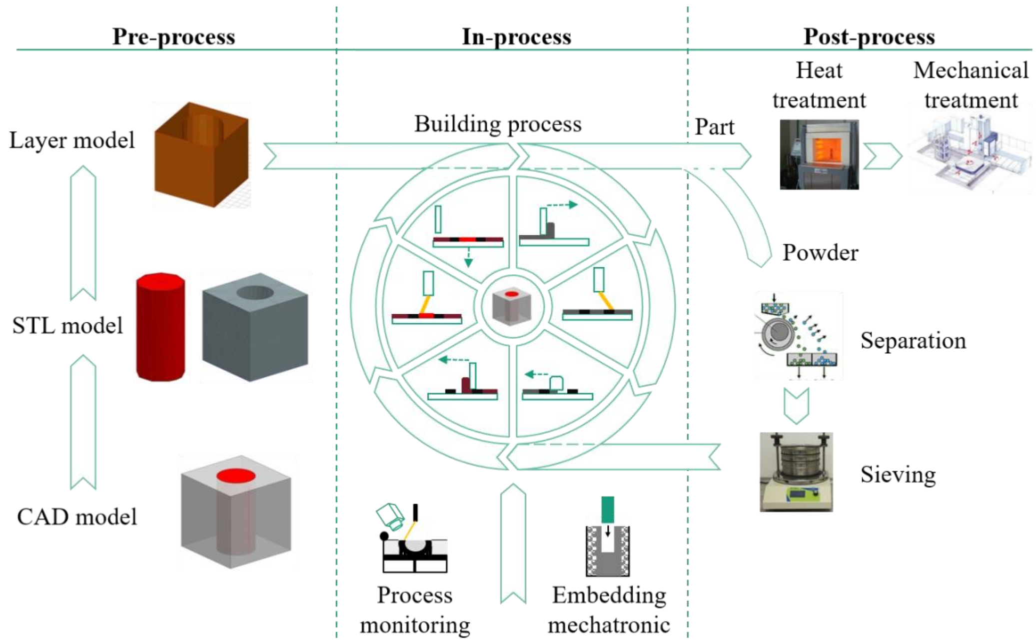

Figure 1: Process chain for (mechatronic) multi-material parts produced using LPBF

Multi-material application: pre-chamber of an internal combustion engine

This section describes a typical multi-material part as an example of possible application areas.

Current part production

Figure 2 shows a pre-combustion-chamber assembly located on a cylinder head. The single assembly units are manufactured separately from specific materials. The first part of the body (dark green cylinder (a) in Figure 2) is used for providing support to the spark plug and to the fuel line, with a non-return valve. This valve is fixed into the cylinder head. Due to its simple construction and its low load conditions, cast iron is used for this part. The second part of the body (yellow (b)) is used to mount the spark plug tip and the fuel line inlet. This portion must be capable of resisting high temperature sparks generated by the plug. Therefore, it is made from stainless steel that can withstand high residual stresses. The first and the second part are joined by brazing or welding. The third body (c) is the pre-chamber tip, which is primarily produced from a material resistant to the high temperatures resulting from the combustion process. Appropriate materials are thermally stable, high-temperature and environmentally resistant, such as nickel-based super alloys. Laser or electron beam welding with controlled depth penetration is used to join the upper body to the pre-chamber tip. [7–9]

Manufacturing through the multi-material process

By facilitating multi-material LPBF [10] it is possible to process two metal materials at the same time in one single layer. The manufacturing of the described pre-combustion chamber can be simplified by manufacturing the first part (dark green (a)) by conventional methods. Subsequently the part is prepared and fixed in the processing volume of the multi-material system. After the creation of a homogeneous powder bed around the base-part, the multi-material process can create the middle part and the complex top (yellow body (b) and grey body (c)) automatically and also allow form closures (instead of graded material transitions), as shown in Figure 2 on the right. Mechanisms such as this are expected to provide improvements in respect of force flow and material transitions.

Additionally, lower assembly and manufacturing costs are anticipated. Through a future expansion of the mechanism with a third material, the manufacturing of the complete pre-chamber part will become possible with an associated further reduction in the manufacturing cost and a functional increase.

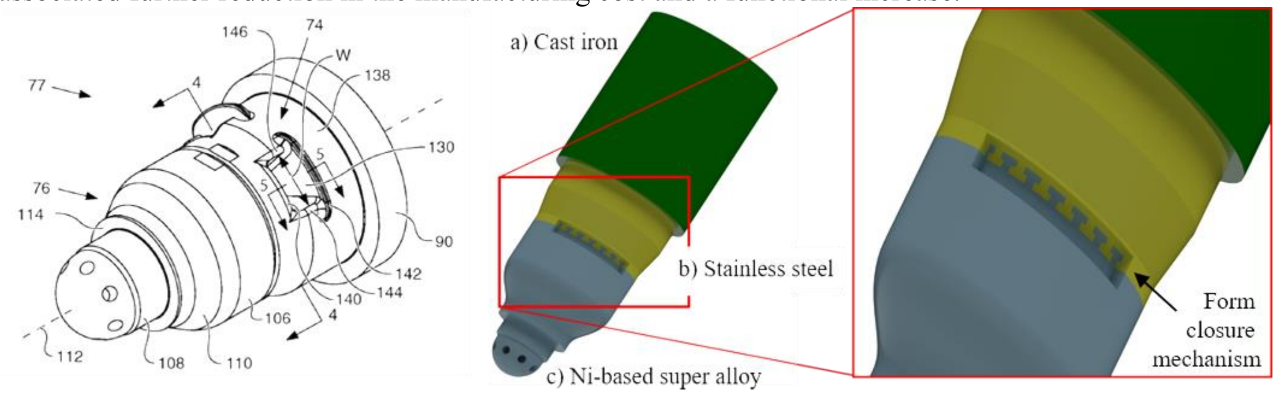

Figure 2: Pre-chamber of internal combustion engine. Left side: Excerpt from patent [7]. Middle and right side: Replica of the multi-material part with visualized material zones. The zoomed view of the right picture shows a possible interlocking between the two material zones to ensure a mechanical force transmission.

Pre-process: data preparation

As already described, process data needs to be prepared during the pre-process. Typically, STL-models are created and sliced into layers of the desired thickness. This data is associated with the material specific process parameters, such as laser power, scan speed and hatch distance. Thus far, however, it has not been possible to assign two different parameter sets to one model, since the STL-model can only represent surface information. Further data, such as material information or definition of any area cannot be included. Thus, each material and parameter set needs to be designed and sliced as a separate model when using STL-file format (see Figure 3, upper block “Current”). This makes data preparation very complex and error-prone. For example, the orientation of one part relative to the other can be displaced. Furthermore, many models must be prepared if a graded material transition is to be created due to the changing parameters after each layer.

First steps towards improving the preparation and being able to assign different parameters within one part require different data formats such as AMF (Additive Manufacturing File Format) described in ISO/ASTM 52915:2016 or the 3MF-format [11] to be used. These formats can include information beyond surface representation and make it therefore possible to assign different parameter sets within one part, e.g. voxel-wise [12]. However, these formats are usually not compatible with LPBF machines and therefore cannot always be used for part production. A potential workflow is shown in the middle block “Prospective” in Figure 3. Through the use of AMF or 3MF-format, time and effort savings during the data preparation are expected, especially because the alignment of different STL files to each other will no longer need to be performed.

Ultimately, future data preparations should be even more advanced (see lower block “Outlook” of Figure 3) because automated embedding of sensors or actuators during the process is expected to be possible by integrated kinematic systems. Ideally, these kinematic systems should receive its moving information (e.g. g-code) from the same data file that also contains the layer model of the part. A more detailed description of how mechatronic systems can be embedded into an AM part is explained later in this work (section: Embedding of mechatronic components into an LPBF part).

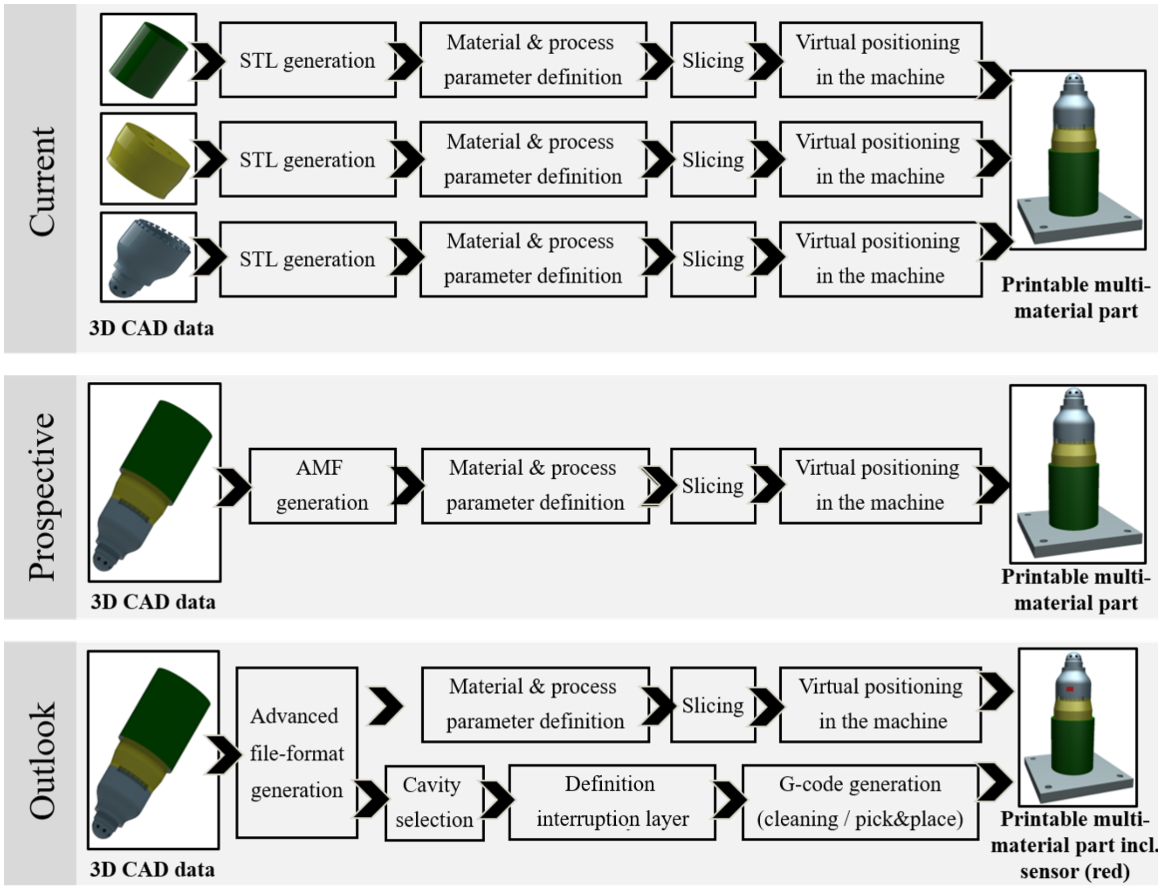

Figure 3: Data flowcharts for the production of mechatronic multi-material parts: current, prospective and outlook.

In-process: process monitoring and embedding of mechatronic components

The in-process step comprises all process steps occurring during the manufacturing process itself. As a result of the latest developments, this also includes the integration of mechatronic parts and the monitoring of the multi-material process with these concepts being focused on in this section.

New requirements for process monitoring

To ensure a correct process sequence and thus the desired component quality, it is necessary to control the defined process parameters and monitor the resulting dynamic process properties (e.g., melt pool or scan track). Where mono-material parts are concerned, more and more machines are equipped with quality control tools that can generally be categorized as either process parameter, powder bed or melt pool monitoring tools [13]. In mechatronic multi-material processing, the number of processed materials increases, sensors will be integrated in the parts or functional parts will be directly build-up during the production process. This results in new requirements for quality control tools because in multi-material production not only can pores and cracks occur but also defects such as cross-contamination of the different powders [14]. This means that almost all the commercial systems of LPBF machine manufactures and approaches from research [15] will have to be adapted or that new methods will have to be incorporated for these requirements to be addressed.
Overall, the effort required for process monitoring will of course increase. Where process parameter control is concerned, the main reasons for this are new or modified mechanisms for powder bed generation [4], different parameter sets required for the various materials [14] and the integration of a handling system for automatic sensor integration.
The challenges in the field of melt pool monitoring occur mainly in interpreting recorded process emissions. Currently available melt pool monitoring systems can correctly measure process emissions and provide them for post-process analysis but are not capable of automatically interpreting the collected data for use in feedback control loops [15]. In particular, the morphology of the transition areas of multi-material components plays a

significant role in defining the mechanical [10] and functional properties and thus requires accurate monitoring. Cross-contamination of powders can result in changes to the melt pool dynamics and favor the formation of defects such as cracks [10].
The detection of this cross-contamination is the main challenge for powder bed monitoring. In addition to deviations from the target state, such as inhomogeneities due to incorrect powder feed or a damaged coating blade [16] that are currently detectable, differentiation between materials in the powder bed will now have to be possible using process monitoring technology. If the optical appearance of materials deviates only slightly between materials, currently used charge-coupled device (CCD) cameras [16–18] reach their limits or the effort involved in subsequent image analysis is significantly increased by the required use of complex algorithms. For this reason, the use of infrared thermography for powder bed monitoring is examined within this contribution.

Powder bed monitoring using thermography

Thermography exploits the fact that objects with a temperature above absolute zero emit electromagnetic radiation, so-called thermal radiation. The decisive factor for material differentiation is that different materials have unequal emissivities. For that reason, materials at the same temperature emit thermal radiation of different intensities [19]. Initial tests were carried out to determine the potential of thermography for this application. For this purpose, a frame for producing defined layer thicknesses was used to manually create powder layers of 35 mm width and 200 µm height on a tool steel build platform. To simulate process deviations, other powders were manually applied on the powder layers and grooves were created. Figure 4 shows a layer of tool steel 1.2709 (X3NiCoMoTi18-9-5) on the left and a layer of cooper alloy 2.1293 (CuCr1Zr) on the right side. The unit digital level (DL) represents a digital value for the energy collected by the detector in terms of photons. The more energy incident on the InSb-detector within its spectral band, the higher the digital count. Each pixel is assigned a color based on the DL value, which can be used to make qualitative conclusions about the emission factors of the materials. A higher emission factor results in lighter colors, because more radiation is absorbed by the material and transformed into heat radiation.

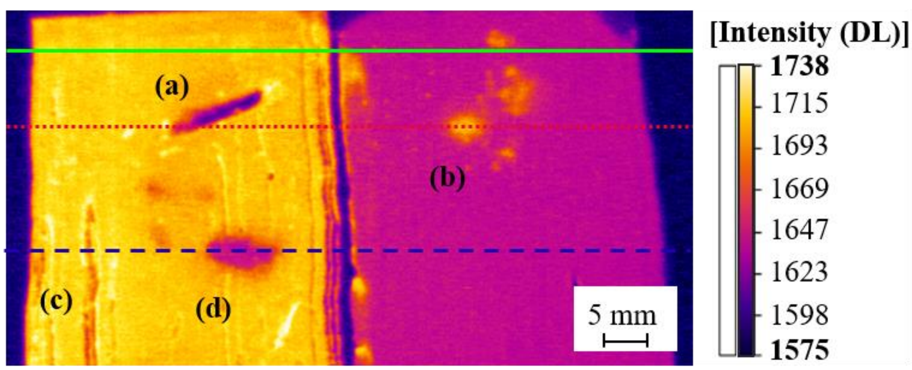

Figure 4: Result of multi-material powder layer monitoring. 1.2709 is applied on the left side and CuCr1Zr on the right. Section of the thermogram of a sample taken with following parameters: 640x512 pixel, 100 Hz frame rate, 0.0003 s integration time. The image represents the radiation 0.09 s after the excitation. (a) defect, (b) 1.2709 on CuCr1Zr, (c) groove and (d) CuCr1Zr on 1.2709. The colored lines in the image represent the positions of the line image analysis, shown later in Figure 5.

In Figure 4 the intensities vary between 1575 - 1738 DL. 1.2709 on the left side shows higher intensities and therefore has a higher emission factor than CuCr1Zr. Visibly higher or lower intensities within a layer can be related to either a deviation in layer thickness or contaminations of the respective powder and thus represent defects. To simulate a data-based evaluation, regions of interest (ROI) were placed over the image. They have the width of a single camera line and simulate a line by line image analysis. Figure 5 (upper diagram) shows the intensity course per pixel of the green ROI from left to right, which represents approximately homogeneous layers of 1.2709 and CuCr1Zr. Small deviations in intensity that occur as a result of camera noise and small differences in radiation absorption due the rough particle surface of the powder layer can be neglected. A significant difference between the intensity of the two materials can be seen.

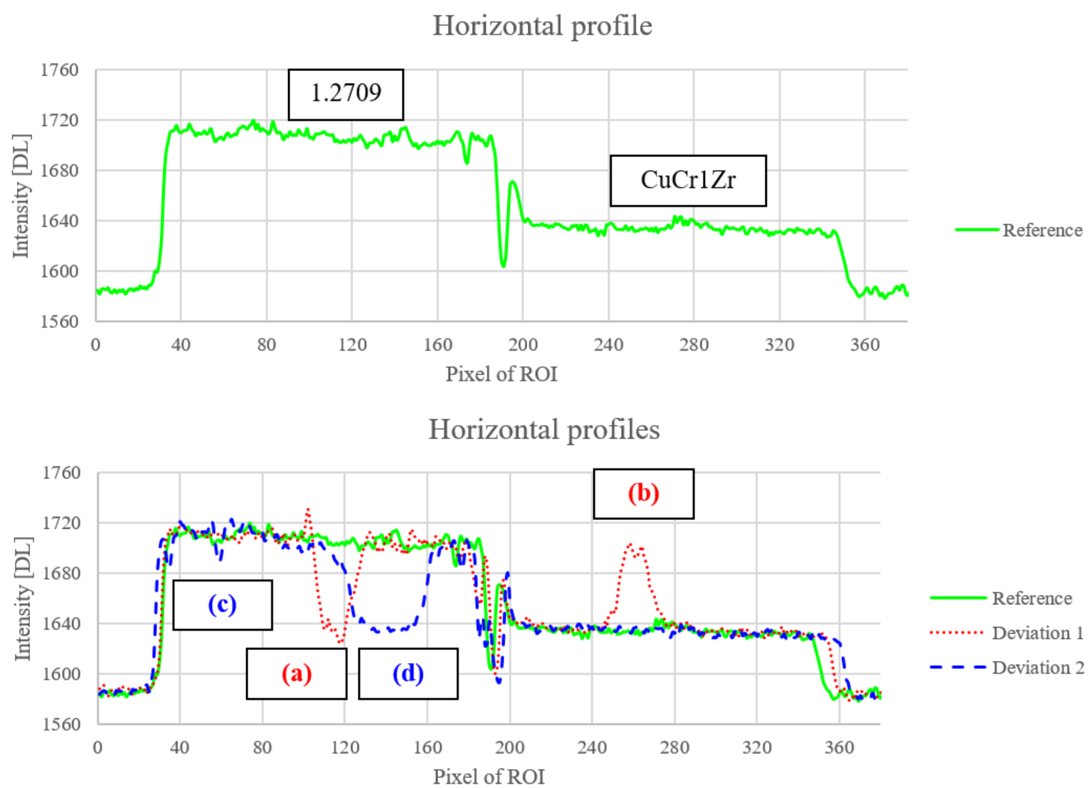

Figure 5: Intensity responses of thermographic pictures. The different graphs are linked to the linear image analysis positions shown in Figure 4. Upper diagram: Different intensity replies of CuCr1Zr and 1.2709. Lower diagram: Effects on the intensity reply caused by defects: (a) defect, (b) 1.2709 on CuCr1Zr, (c) groove and (d) CuCr1Zr on 1.2709.

Figure 5 (lower diagram) shows two ROIs with defects, which are compared to the reference of the upper graph. Differences in layer thickness lead to different cool down rates. 0.09 seconds after the excitation, areas with lower layer thickness have already cooled down or emit less heat radiation. The intensity values of defect (a) and (c) are lower than the directly surrounding environment and therefore show the described behavior. Cross-contamination also leads to different intensity values, but those are linked to the emission factor of the materials. As already mentioned, 1.2709 has a higher emission factor then CuCr1Zr. Therefore, defect (b) leads to an increase and defect (d) to a decrease in the intensity values.

Between 0.10 s and 0.50 s after the excitation, the whole layer cools down and even little deviations in layer thickness can be detected. This behavior is expected for thin layers, as heat can be dissipated relatively well. With increasing thickness of the powder bed, heat dissipation decreases, as the air inside the powder bed acts as an insulator. To investigate the thermal reaction of powder with increasing thickness more closely, a test stand will be set up that will enable the production of a powder bed. In addition to the active approach, monitoring by means of passive thermography is also examined. Most LPBF systems have a building panel heating system to reduce internal stresses in the assembled component. The powder is preheated from below, which could make external excitation unnecessary.

In addition to powder bed monitoring, there are other potential applications for the use of thermography for in-process control. It has already been used passively for melt pool [20], scan track [20–22] and layer monitoring [23, 24]. An approach for future investigation is the use of active thermography to detect near-surface defects, such as lack of fusion. These defects have a significant influence on the components' mechanical properties and are caused by already known [25, 26] as well as unknown process deviations [27]. The ability to monitor the structure of already solidified layers would open up new approaches for process control.

Embedding of mechatronic components into a LPBF part

Layer-upon-layer build-up methods can be used to integrate other components, such as sensors, into a construction part. In 2011, Sehrt and Witt integrated a radio-frequency identification (RFID) chip into a stainless steel part and demonstrated its subsequent function [28]. Indeed, actuators such as a piezoelectric multilayer actuator for dynamic applications have already been incorporated inside a LPBF part [29]. In addition, [30] performed a survey on links between additive manufacturing and sensor integration in order to analyze advantages of additively manufactured mechatronic parts and corresponding applications.

The layer-upon-layer build-up of AM makes it possible to embed components during the manufacturing process. For successful implementation of a component several steps must be considered, depending on the aim and the part application. Despite multiple relationships between the single steps, the preparation can be abstracted to a general procedure model (using the example of sensor components) that is presented in Figure 6. This model is based on experience from several projects in the field of component integration using the LPBF process and is in this case focused on the insertion of sensor components. It can be used as an extension of the basic classification according to VDI 3405 which divides an LPBF process into pre-, in- and post-process [3].
The plan to insert a sensor into a LPBF part starts with the selection of a component part (compare Figure 6), which defines the dimensions as well as the material. In addition, the requirement of sensor information at a specific position must be selected. The part geometry further determines the space for the sensor (based on the assumption that the part size should not be modified) and therefore restricts the applicable sensor types. In selecting a sensor type, a distinction can be made between active and passive sensors, which is relevant because active components can operate without an auxiliary energy supply. Accordingly, active sensors are suited for long-term autonomous operations and are thereby predestined for wireless communication methods. Passive sensors require an external energy supply, which normally means conductors must be provided. Thus, these sensor types are usually integrated with cables, which implies a requirement for preassembled wires or the application of electrical contacts during the process e.g. by building them up during a multi-material LPBF process (requirement of three materials: structural, insulating and conductive material). The LPBF process conditions can be described as harsh for a sensor system. High temperatures as well as electrically conductive powder contamination can potentially disturb the smooth functioning of the sensor system. A protection method is therefore indispensable, especially from the high temperatures resulting from the laser-induced melt pool. In Figure 6 three approaches are introduced ("environment protection"), which can shield a mechatronic system from this temperature load. Possible ways for creating a temperature insulating system are the deposition of several powder layers over the sensor before the cavity is closed.
Otherwise it is possible to insert an additional plate on top of the sensor (as shown below in Figure 7) which absorbs the high energy or a prior embedding of the sensor system into a resin or polymer of low conductivity. After the selection of a protecting method, the sensor can be inserted manually or ideally by an entirely automated system, which means an operator is not required. The last preparation step, which is critical for the success, is the cavity design. Ideally, it provides the space where the sensor will be inserted, a force fit sensor mounting and also takes into consideration communication requirements, such as a thin wall to enable trouble-free wireless communication.

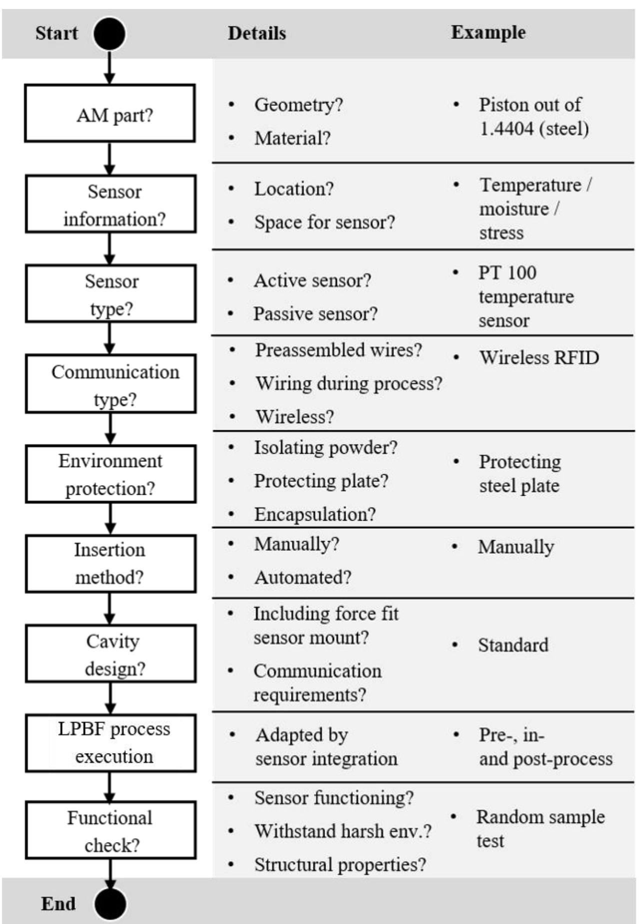

Figure 6: Procedure model for the integration of mechatronics into LPBF parts, using the example of sensor components

Then the conventional LPBF process (including pre-, in- and post-process) can be performed, until the hybrid part has been manufactured. Due to the high risk of failure and to ensure the functioning of sensor systems, a functional check of the AM part is useful to ensure it will function correctly in the intended environment.

Case study – integration of a DC-motor into a LPBF part

Figure 7 describes an example of the integration of an actuator component. Initially a conventional LPBF process was started and then interrupted at defined layer x. The intended cavity is cleaned manually and a DC-motor (type: Motraxx 2025-22) is inserted. The wiring of the motor was preassembled and the motor was protected by a metal plate to avoid damaging through the high temperature. Using an additional metal block inside the cavity, the motor has a form-fit mounting inside the cavity. The outgoing wires are embedded in the surrounding powder bed. The process continues and results in a rotor system with a fully integrated DC-motor. By way of example, two different DC-motors have been integrated using this process with the same method. Both systems are performing trouble-free and can be powered by a 1.5 V battery. To what extent disadvantages such as difficult accessibility to the motor for cleaning or repair purposes outweigh the advantages of complete encapsulation still needs to be clarified for various applications. The rotor, shown on the right side of Figure 7, was additionally manufactured by LPBF and mounted afterwards.

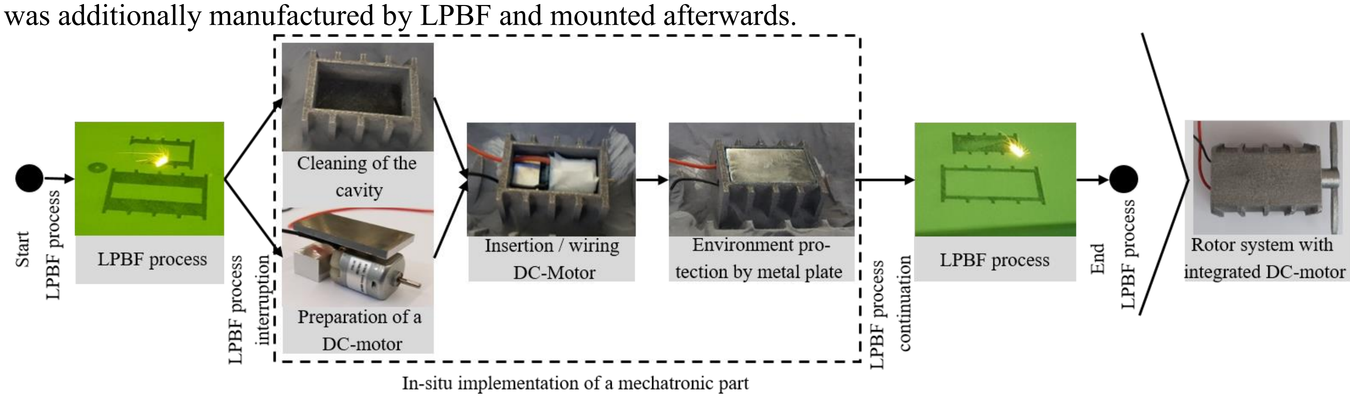

Figure 7: LPBF in-situ incorporation of an actuator into an LPBF part (material: AlSi10Mg)

Post-process: powder separation

Post-processing procedures of parts from multi-material LPBF differ from that of mono-material LPBF parts. For instance, the thermal treatment needs to be adapted to given material combinations. This means developing new process parameters for treatments compatible with both materials on a single case basis. The same applies to surface treatment of multi-material LPBF parts. The process chain itself however does not change in both cases. By contrast, the same does not apply to the recycling of the processed powder materials. Irrespective of the applied multi-material coating mechanism [2], as long as two or more different materials are processed in one build job, critical cross-contaminations that might cause structural defects cannot be excluded [31–33]. Thus, the powders need to be separated and reconditioned during a recycling process. To identify relevant separation principles, the powders used in multi-material LPBF must be characterized. Firstly, the initial situation after the build process and prior to powder separation should be investigated. Secondly, a review of common material and powder properties needs to be conducted in order to determine existing differences for separating principles to work with. Starting with the first step, Figure 8 gives an overview on different positions within the process chamber where powder materials were mixed as well as the corresponding mixing ratios. With maraging steel 1.2709 from the rear powder collector (position C) showing the highest coefficient of variation CV = 5.7 % of given test series, the results can be seen as robust and conclusive. Differences in material mixing ratios are explained by the order of processing of materials during the build job. Reference [10] has shown that the scanning order strongly depends on the processed material combination. For 1.2709 and CuCr1Zr, part properties are superior if the tool steel is solidified first and CuCr1Zr second, compared to the other way around. In addition, the mixing ratio depends on the scanned area. The more material is solidified, the less remains in the powder bed (B) or is removed by the vacuum unit (D) [10]. The material composition and its range of mixing ratios however show that the powders cannot be re-used directly after the build job. Instead, the powder materials need to be separated before entering the standard recycling process in accordance with [34]. Consequently, the next step is to identify relevant powder separation principles.

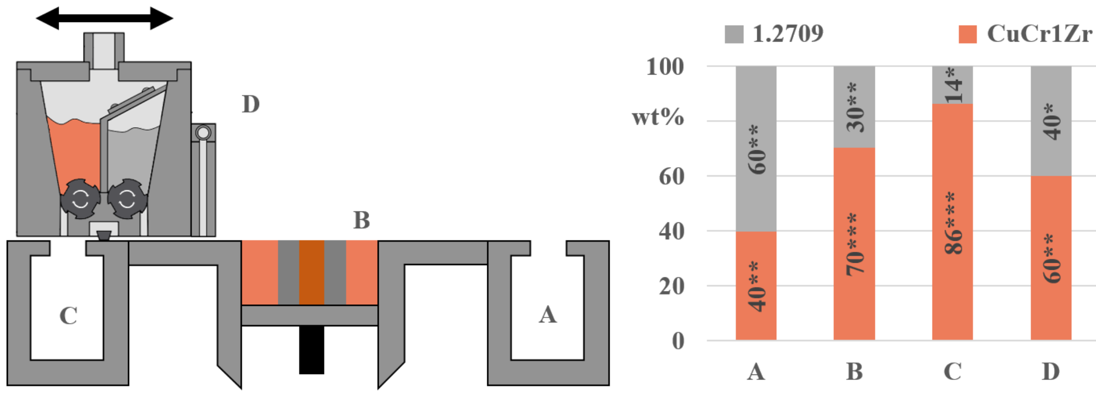

*Figure 8: Schematic representation of the multi-material LPBF process chamber (left) and quantified results of the mixing ratio analysis of different positions within the process chamber (right). *: 10 % ≥ CV > 5 %; **: 5 % ≥ CV > 1%; ***: 1 % ≥ CV. The built part consists out of 50 wt% 1.2709 and 50 wt% CuCrZr.*

As these separation principles always depend on differences in physical, chemical, thermal, electrical or other material properties [34], an overview of potentially occurring differences in named properties for powder materials used in multi-material LPBF is needed. References [35–38] serve as a basis for listing relevant material and powder properties that commonly occur in LPBF. Table 1 summarizes the results and explains which properties are expected to lead to promising separation technologies. Consequently, separation technologies based on density, magnetizability, particle size, particle surface and particle inertia should be investigated in detail.
The key parameter for evaluating the chosen separation technologies is selectivity. Moreover, depending on the achievable discriminatory power, implications for quality control along the powder process chain must be derived to achieve consistent mechanical properties for final parts produced by multi-material LPBF.

Table 1: Overview of relevant material properties to identify respective separation principles

Properties		**Expected applicability**	**Explanation**
Material properties	Density	Good	Broad range of materials and corresponding densities from Magnesium (1.74 g/cm^3) [39] to Tungsten (19.25 g/cm^3) [40] can be processed via LPBF
	Reflection	Poor	Detection of and distinction between polymers, ceramics and metals possible but challenging semi-automatic separation due to particle size
	Electric conductivity	Poor	No separation principle was found based only on electric conductivity
	Thermal conductivity, expansion & capacity	Poor	No separation principle was found based on named thermal properties
	Chemical stability	Poor	Preciuos metals could be recovered from less precious ones by dissolving the latter in strong acids; despite losing one material this could be relevant for expensive precious powder materials
	Magnetizability	Good	Magnetic separation for LPBF powder materials already applied by [6]
	Melting point	Poor	Despite general applicability, one material would be lost during the separation process, which makes melting less favorable
	Plasticity	Poor	No separation principle was found based on properties like plasticity or ductility
Particle properties	Particle size	Good	Reference [41] suggests to use different particle size fractions in multi-material LPBF so that the powder can be separated by sieving
	Particle shape	Poor	High particle sphericity is desired for all LPBF powders as differences in shape can lead to structural defects [42]
	Particle surface	Good	A number of separation techniques based on wettability exist [34], rough particle surfaces however lead to decreased powder flowability which can lead to inferior final part properties
	Particle mass	Good	If similar particle size distributions are used for all processed materials, for particle mass the same applies as does for material density, furthermore particle inertia is a common separation principle [43]

Conclusion and outlook

Selected results in the field of mechatronic part production by means of metal-based multi-material LPBF were presented in the context of this work. Initial progress in the areas of data preparation, process monitoring, sensor/actuator integration and powder recycling illustrate the challenges but also the potential of the individual developments. Upcoming research in these areas should aim to further develop the technologies to the point where they can be transferred into products for industry. Therefore, the relations of material properties and process parameters as well as the influence of different material properties within one building process must be examined in more detail. The analysis of individual layers and the detection of defects must be further investigated in order to be able to identify defects automatically. The integration of mechatronic components should be automated through a kinematic system in future work, which would have the advantage that process interruptions and manual work during the building process can be prevented. However, automatable solutions are still to be developed for current challenges, such as the thermal stress induced by the LPBF process, the mechanical fixations of components or the suction of powder for the production of the cavity. There is also a need for research in respect of powder separation. Depending on the powder mixture defined in terms of the mixing ratios and material properties of the powders involved, a number of different challenges arise, with the two most important ones being similarity of mixed materials and the need for high selectivity. Thus, the previous section characterized powder mixtures as they occur during the application of a multi-material LPBF system developed by Anstaett et al. [4, 6, 10]. In addition, properties of metal powders commonly used in LPBF were identified in order to pre-select relevant separation principles for multi-material LPBF powder mixtures. This needs to be investigated further for the purpose of separating the most relevant powder combinations.

Acknowledgements

The authors extend their sincere thanks to the Bavarian Ministry of Economic Affairs, Energy and Technology for providing the financial resources for research within the "Multi-material Centre Augsburg" project of which this paper forms part.

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