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Development of an Automated Process Chain for Hybrid Additive Manufacturing using Laser Powder Bed Fusion

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Abstract

Additive Manufacturing (AM) offers great potential for producing complex parts. However, the economical fabrication depends among others on the part height. Hence, the combination of a conventionally manufactured base body and AM offers potential to reduce part costs. This combination is called Hybrid Additive Manufacturing (HAM) and requires additional clamping mechanisms and a positioning system in the laser powder bed fusion process. Concepts for both requirements will be investigated within this paper. In order to increase flexibility and automation a concept for an automated process chain will be developed. The requirements and properties of the process chain will be discussed.

Keywords: Hybrid Additive Manufacturing; Automation; Subtractive Manufacturing; Clamping; Positioning; Metrology

1. Introduction

Rising demands on the performance and production costs are affecting the production of parts significantly. Additive Manufacturing (AM) is one of the key technologies of modern production due to its freedom of design and the ability to manufacture near net-shaped parts in one process without tooling. Laser-based powder bed fusion of metal (PBF-LB/M) is one of the AM technologies gaining relevance in research as well as in industrial production. [1, 2]

The term Hybrid Manufacturing (HM) is not consistently defined. In general, Hybrid Manufacturing is described by the International Academy for Production Engineering (CIRP) as the combination of at least two manufacturing technologies or materials used to manufacture a component. The combination is specified to be at the same time or at the same area of the component [3]. Zhu et al. provides a review on HM and describes Hybrid Additive Manufacturing (HAM) as an AM process with subsequent machining and as an approach for Multi-Material [4].

For classification in this study Hybrid Manufacturing is defined as:

- An additively manufactured part is built on top of a pre-manufactured base body.
- The base body is produced by a different manufacturing technology (subtractive manufacturing, e.g. turning and milling, casting or another additive manufacturing process) [5, 6].
- On top of the base body, laser-based powder bed fusion of metal is utilized for further processing. In Fig. 1 this structure of a HAM part is displayed.

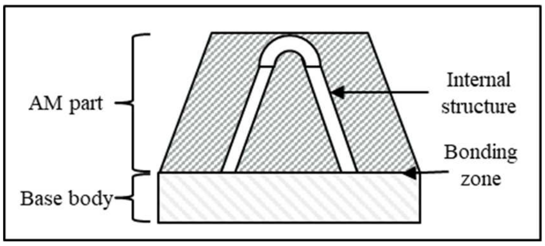

Fig 1: Basic structure of studied Hybrid Additive Manufacturing process with base body and AM part joined in the bonding zone is illustrated.

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The base body (pre-manufactured by e.g. turning) and the internal structure (enabled by AM) are joined by remelting in the bonding zone [7].

Referring to the terminology of Additive Manufacturing (DIN EN ISO/ASTM 52900), this manufacturing process is called by the authors hybrid laser-based powder bed fusion of metal (PBF-LB/MH) [8]. The process chain of PBF-LB/MH is illustrated in Fig. 2. Compared to regular PBF-LB/M additional and modified steps are highlighted. For this approach of HAM a regular PBF-LB/M machine will be used, so the layer-wise in-process is not modified. Subsequent final machining and heat treatment is possible. This will be summarized as post-process and will not be considered in this research.

A HAM process enables higher resource efficiency and allows customized, functionalized parts as well as repair applications [9–12].

Since PBF-LB/MH needs additional steps especially in the Pre-Process, for a higher efficiency automation is necessary. After a literature review concerning HAM, concepts for the most manual working steps (clamping and positioning) for an automated process chain will be discussed.

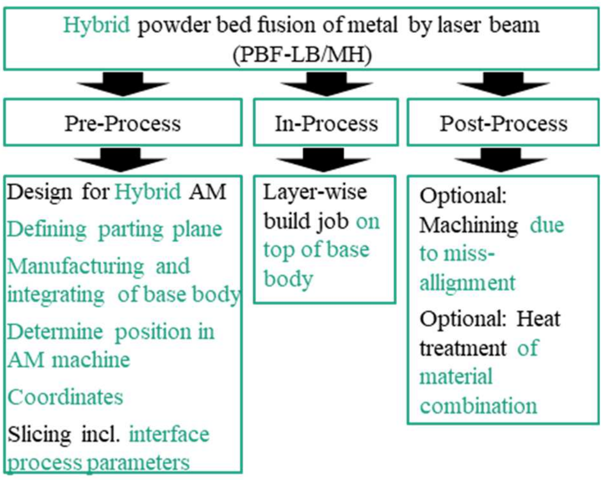

Fig 2: Overview of PBF-LB/MH process with highlighted additional or modified parts compart to regular PBF-LB/M.

2. Literature review

Research concerning HAM has been conducted with different combinations of conventional (turning, milling, forming, casting) and additive manufacturing technologies (direct energy deposition: powder and wire-based, PBF) [13, 14].

Lutter-Günther et al. developed a price model for the combined use of Laser Metal Deposition (LMD) and subtractive manufacturing. It can be adjusted and evolved for other combinations of HAM. [15]

There can be two main benefits identified by utilizing PBF-LB/MH:

- Reduction of AM processing time and resources: Cost efficient production of repeating base bodies by conventional manufacturing and complex structure by AM on top of it.
- Reduction of conventional machining: Only simple geometries are produced by conventional manufacturing. Machining time is minimized by adding features with AM and flexibility is gained.
- Repair of worn-out parts: Repairing can extend the parts lifetime and reduce costs and material for fabricating a new part.

In the following, examples of hybrid process chains in research are mentioned:

The high volume deposition rate of wire arc welding (WAAM) is utilized to reduce the subsequent milling as finishing step [16].

Penchev et al. developed a clamping platform for PBF by modifying a baseplate with a chuck. This enables to keep the positioning reference along the whole process chain. Every machine in the process chain needs to be equipped with this chuck. A routine is described for measuring the off-set when switching the machine by scanning/metrology methods [17, 18]. With this platform, Bhaduri et al. investigated the bonding zone of hybrid aluminum parts and Mehmeti et al. the combination of MIM and PBF parts [6, 7].

Ahuja et al. investigated AM of Ti6Al4V on metal sheets. For fixing, a deep drawn metal sheet the build platform was modified with a punch geometry, clamping sheets and a platform reduction plate. [19, 20]

There are a few industrial providers, utilizing PBF-LB/MH for their products:

Komet describes the principle of manually defining the parting plane between conventional and additive part to reduce the building height of diamond equipped high-performance tools. In some cases, they are not directly joined with the base body but fixed afterwards by screws [21]. Neher is customizing and functionalizing conventionally manufactured base bodies, which are standard, recurring geometries such as tooling interfaces and medical implants [22]. Mapal is using PBF to build on top of general machine interfaces with the necessity for conventional post processing to ensure accuracy between interface and tool [23]. Rosswag adds geometries with PBF to high volume base bodies, manufactured by forging [24].

All of the examined literature gives some clue for the necessity of clamping the base body inside the PBF machine. As far as the authors are informed, only Penchev et al. give a more detailed view on how the clamping is implemented for gaining flexibility and accuracy. Metrology is necessary before the build job for alignment of the two parts and afterwards for quality measurement (QM). [17, 18]

One approach eliminating these modifications to the AM machine is to use a specialized HAM machine. There are two principles to be mentioned:

Matsuura provides a PBF-LB/M machine with integrated milling between the layer-wise process, though it will be built upon a regular build plate and not a pre-manufactured base body [25]. DMG Mori provides a laser metal deposition machine with integrated switchable milling tools [26]. In both cases, aligning the coordinates between subtractive and additive manufacturing is included inside the machine control, since no change of position or re-clamping is necessary. A drawback concerning effectivity is that in this approaches one process is always paused, since both manufacturing technologies are combined in one machine.

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To summarize the literature review: A good overview of HAM in research and industry is available and the potentials and applications are well studied. For further application and reduced cost and effort, flexible, automated and reproducible concepts for a hybrid machine/the hybrid process chain are necessary and will be discussed in the following section [27, 28].

3. Results and Discussion

3.1. Concept of an automated process chain

In Section 1 an overview of the process chain in PBF-LB/MH is displayed (see Fig. 2). In this section, it will be focused on the non-value-adding process steps with high demand for automation. In Fig. 3 the pre-process is divided into physical and digital process chain. Here it will be focused on the physical process chain and how it needs to be linked with the machine set up and the digital process chain. The key aspects are the following:

- For a dense and crack free bonding zone, process parameters for the material combination need to be investigated and utilized in the bonding zone. The bonding zone (see Fig. 1) and its influence on the part quality is studied in several researches and will not be taken into account here [7, 29].
- After interviewing service providers offering PBF-LB/MH it has become clear, that no sufficient solution for clamping and positioning the base body is available. Developing an own solution can be cost intensive and typically results in specialized, inflexible solutions for a certain use case. Requirements and concepts for a flexible clamping system will be discussed in section 3.2.
- The position of the base body in the physical world needs to be fitted with the coordinates of the AM-process (in PBF-LB: The coordinates of the laser related to the position on the build platform). Requirements and concepts for a measurement system will be discussed in section 3.3.

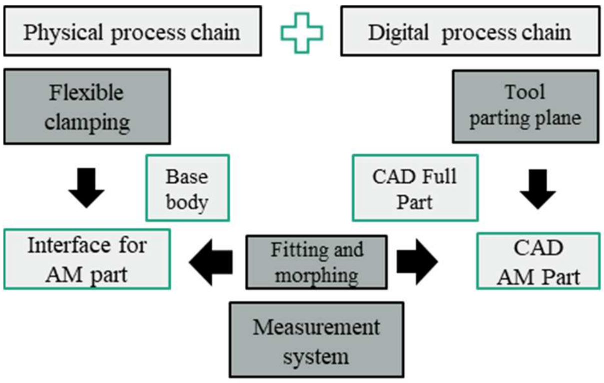

Fig. 3: The hybrid process chain is divided into digital and physical world. It is linked by the measurement system for fitting and morphing.

For realizing an automated process chain, a consistent software is necessary. The following steps can be potentially included or linked with software interfaces to 3rd party applications:

- Defining the parting plane between conventional and additive manufacturing.
- Slicing the AM part and adjusting the digital position to the physical and assigning the AM process parameters to the bonding zone of the AM part.

The automated software process chain will be discussed in future research and only key requirements are described here. The software solution needs to be fitted to the design process, since HAM is adding opportunities for the design and new use cases. [9]

The demand for more flexibility and reduced setup time depends on the application and the user. It will be distinguished between two scenarios:

- HAM on top of base bodies with similar and recurring geometries. It can be the serial production of new parts or repair applications. Flexibility is subordinate to high productivity and short setup time. This could be relevant for an OEM.
- HAM on top of varying base bodies with differing geometries. For economically manufacturing these varying parts high flexibility and productivity is required. This could be relevant for a service provider or repair applications.

3.2. Clamping of base body

In PBF-LB/M the AM part is built directly on a base plate which is fixed to the machines build platform by screws. In PB-LB/MH instead, a base body needs to be positioned. Since the build platform only provides threads for fixing the regular base plate additional concepts for fixing and positioning must be provided, comparable with clamping systems (CM) in subtractive machining. The following requirements for a concept are identified and marked as must- (M) and optional- (O) criterion:

- The CM can be integrated into the limited building chamber of a regular PBF-LB/M machine. The concept can be transferred to another machine. (M)
- The CM is in direct contact with the metal powder and needs to be resistant against the feedstock and the gas atmosphere. This may be realized by the CM or a sufficient sealing has to be applied. (M)
- Residual powder needs to be removed to avoid cross contamination of the feedstock, so it needs to be accessible and cleanable. (M)
- The higher the CM, the more build height is lost and should be minimized. (O)
- Depending on the metal powder, pre-heating from the build platform during the whole process is necessary. The temperature can be up to 200°C for regular and up to 1000°C for high-temperature PBF-LB/M. Some materials don't need pre-heating. If pre-heating is necessary, the CM needs to be temperature-resistant and needs to transfer the heat from the build platform to the base body surface. (O)
- For a most flexible CM different geometries, dimensions and numbers of base bodies can be fixed. The demand for

flexibility is depending on the use case (e.g. series production with recurring base body, see section 3.1). (O)

Referring to subtractive manufacturing, different concepts for fixing the base body are compared regarding their capability for PBF-LB/MH. An excerpt of the analysis is given in Table 1.

Table 1: Excerpt of the analysis of technical concepts for clamping. Qualitative rating: -- very negative for process chain, - little drawbacks, + some advantages, ++ much advantages

Technical concept for clamping	Effort at setup/infrastructure	Accuracy/ Reproducibility	Flexibility
Hydraulic/ Pneumatic	--	+	+
Magnetic	-	-	++
Thermal	+	-	+
Mechanical	+	+	+

If only low flexibility is necessary, part specific adapters are utilized for an easy implementation with high reproducibility alignments, such as fitted pins and exact manufacturing tolerances lead to high accuracy of positioning the recurring base bodies. Since the process chamber is sealed, concepts with no additional medium are preferred (thermal and mechanical clamping). If high flexibility and low accuracy is required, clamping by thermal expansion is one option to realize. Another solution for high flexibility is magnetic clamping. Min. part size, max. temperature and utilized materials need to be considered for implementing a magnetic clamping system. A good balance for higher accuracy can be a mechanical clamping concept, such as integrating a chuck or a centric clamping vise.

There are already a few clamping concepts available specialized for PBF-LB/M. Most of them are miniaturized zero point clamping systems. They can be heated up to 200°C, are resistant against metal powder and can be implemented in modular ways. They all have the drawback to be developed for fast fixation of base plates, so hybrid base bodies need additional modification on their bottom for fitting to the clamping spigot. This can be a hindrance for the design.

One concept for a semi-flexible clamping with high accuracy and reproducibility is currently in development. The principle is based on adapting a clamping vise on to a PBF-LB/M build platform (Fig. 4).

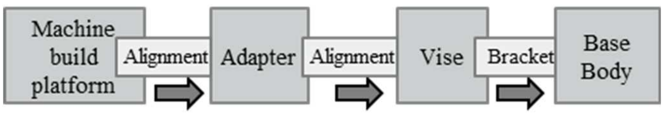

Fig. 4: Concept for a mechanical, semi-flexible clamping with alignments (e.g. pins) for accuracy.

3.3. Metrology and positioning

A clamping system with high accuracy can already include the function of a reproducible positioning. This would be the case for zero point clamping systems. When higher flexibility is necessary, less exact positioning is realized by the clamping system, thus an additional metrology system is necessary. The accuracy of the positioning depends on the application. It can differ between 1 mm and <0.1 mm. Besides translational shifting parallel to the working plane, a tilted base body due to poor clamping needs to be identified by the measurement system.

The following measurement systems are compared for utilizing in PBF-LB/MH:

- Melt-pool-monitoring systems are designed for in-process quality assurance in PBF-LB/M [30]. Since it is on-axis of the laser beam and already implemented inside a SLM 125 HL, it is tested for determining the positions of base bodies. Instead of receiving the emission of the melt pool, the concept is to distinguish between background and base body by stimulating the surface with the laser beam. It is still experimental and needs further research for finally evaluating the concept.
- Active thermography is a technology for quality inspection and is investigated to be in a comparable way like melt-pool-monitoring [31].
- 3D scanning with structural light (blue light) is a method for quality inspection and is used for benchmarking AM processes [32]. Siemens energy is using the technology in their PBF-LB/MH process for determining the position of the base bodies related to the clamping system [10]. Due to the size of the system, measurements need to be conducted outside of the machine. Further research is needed in order to measure the base body/bodies in clamped position inside the PBF machine. This would eliminate extra steps in preparing the hybrid build job and reduce the expense of correlating the coordinates in-/ and outside of the machine.
- CMOS cameras are easy to implement inside the process chamber in PBF-LB due to their small size. The 2D image processing with edge and position detection is flexible and scalable according to the requirements of the use case. The use of open source software helps implementing and transferring the system to other machines.

In table 2 an excerpt of the analysis is displayed. The highest flexibility and accuracy is possible right now with a well calibrated 3D scanning system. The drawbacks are the high costs of the system and due to the size and working distance/angle the hindrance of implementing the system inside the process. This can, on the other hand be achieved by a 2D camera system, which can be fitted for the AM machine and can be set up and mounted according to the requirements. This approach will be investigated in the future.

Table 2: Excerpt of the analysis of technical concepts for measurement system. Qualitative rating: -- very negative for process chain, - little drawbacks, + some advantages, ++ much advantages

Metrology concept	Effort at setup/infra-structure	Accuracy/ Reproducibility	Flexibility
Active thermography	--	-	+
Melt Pool Monitoring	-	-	+
3D Strucured light scan	+	++	+
2D Imaging, edge detection	+	+	++

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In Fig. 5 a first demonstrator is displayed and implemented into the process chamber of a SLM 125 HL. The camera and mounting system (portal tripod) can be changed easily.

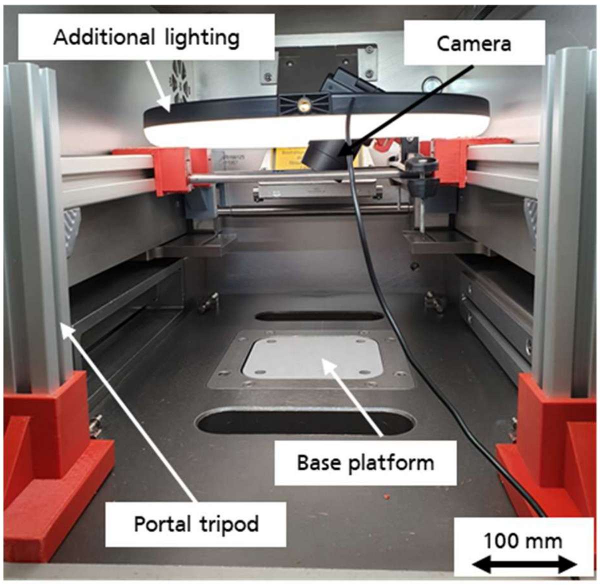

Fig. 5: Demonstrator, which is currently in development is implemented into the process chamber of a SLM 125 HL machine.

4. Conclusion and Outlook

A literature review concerning the current state of Hybrid Additive Manufacturing is given. Since Hybrid Manufacturing is a very broad and ambiguous used term, hybrid laser-based powder bed fusion of metal on top of a base body is defined (PBF-LB/MH). This leads to customizing the conventional PBF-LB process. Additional clamping is necessary for fixing the base body. For determining the physical position of the base body and aligning the digital position of the AM part a measurement system needs to be implemented into the process chain. Depending of the scenario (serial production or highly flexible service provider) the right clamping and measurement system needs to be identified according to the needs for the process chain.

The following was achieved and adds value for further research:

- Overview and demands for hybrid process chains are found and utilized for developing a solution, which is capable of high automation.
- Clamping mechanisms are compared. The mechanical clamping is a promising concept for high accuracy and a semi-flexible clamping, whereas magnetic clamping provides the highest flexibility.
- Measurement systems are compared and analyzed for implementing into the PBF-LB/MH process chain. A 2D camera system features high flexibility with scalable accuracy. Due to available open source software, it can be transferred to other machines, too.

Looking at the results the following topics need to be investigated in further research for a solution suitable for research and industrial applications:

- Evaluating a process chain including pre-, in- and post-process as well as QM of a demonstrator part.
- The hybrid process chain needs to be evaluated economically and compared with a conventional or additive process chain.
- After implementing the process chain in one machine, it needs to be transferred on another PBF-LB machine for retro-fitting.

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