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Concepts for integrating laser polishing into an additive manufacturing system

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ABSTRACT

With the introduction of Additive Manufacturing, many industrial sectors benefit from the freedom of design and capabilities of this technology. Components can be individually designed and extended with different functions. However, high effort in the post-processing is necessary, since surfaces have to be processed and support structures have to be removed. This post-processing usually takes place outside the Additive Manufacturing machine. Therefore an additional effort is necessary for the machining process, but also for pre- and post-processing of the components. For example, positioning in a CNC milling machine has to be done. It is not feasible to fabricate complete systems consisting of multiple components in a single manufacturing operation.

Especially optical systems require high surface qualities. The surfaces usually have to be milled or polished. In order to install the optical system afterwards, an enormous adjustment and assembly effort is needed. This can be bypassed, when both optics and mechanics are manufactured during the same process. However, integrating subtractive post-processing should be avoided as it may cause contaminants that cannot be removed from the system. Transformative processes like laser polishing do barely cause contaminants and are more suited for parallel processing.

In this work the integration of a laser polishing system is evaluated, which can be used to reduce surface roughness. The requirements for the light source, manufacturing accuracy, etc. are clarified and concepts, how the integration can be implemented are developed. In addition, possibilities for processing additional materials to manufacture optical systems in one machine are discussed.

Keywords: Additive Manufacturing, laser polishing, integrated optical components, hybrid manufacturing

1. INTRODUCTION

For some years now, additive manufacturing has occupied a growing position in many branches of industry and in science. The processes of additive manufacturing are among the main pillars of the objective of industry 4.0, often referred to as the fourth industrial revolution. They offer the possibility to directly produce industrial parts from 3D-CAD files and above all to economically implement the approach of customer-specific production. Additive manufacturing creates new possibilities for the design space in relation to conventional manufacturing procedures, whereby the manufacturing expenditure does not rise necessarily with increased complexity of the geometry of components or systems. [1,2]

This freedom of design is already being exploited in the field of optical technologies and in particular in optomechatronics, but the area of application extends mainly to individual polymer-based components and the processing of glass. In order to be able to contribute further potentials to additive manufacturing, it makes sense to adapt the design of optical components in such a way that several tasks can be performed simultaneously through functional integration, thus reducing the size and weight of an optical system. At the same time, it is possible to manufacture not only individual optical components, but entire optical systems that contain a multitude of functions. However, certain functional combinations, such as thermal conductivity paired with electrical insulation, can only be implemented using specific material classes, which make the use of several materials in the optical system unavoidable. [3,4]

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Therefore the necessity for multi-material additive manufacturing (MMAM) arises. However, both the production of functionally integrated optical components and the production of optical systems are subject to production-related limitations which can reduce the optical quality.

The main problem is the geometry of the components. Due to the freedom of design and the associated free-form geometries, open cavities or undercuts can occur, which means that access for finishing processes such as milling or polishing is no longer guaranteed. The cavities do not have to represent optically functional surfaces, but a certain surface roughness may be required, which can only be achieved by post-processing. Thus, functional optical surfaces (refractive and reflective) have to be manufactured additively with a sufficiently high quality, which is not possible with current additive manufacturing processes. Therefore, the post-processing must take place as long as the functional surfaces are still accessible. A parallelization of the process steps production and post-processing is therefore unavoidable and leads to the idea of a hybrid production machine.

Requirements for the post-processing have to be considered, which among other things include that during the process no contaminants may arise which could have a negative effect on already processed optical surfaces. If the processes are divided into subtractive, additive and forming processes, it makes sense to integrate forming processes into an additive manufacturing machine, since this neither leads to material removal nor to additional material supply for post processing. An example of such a forming process is laser polishing.

In this work, concepts are developed which represent possibilities to construct such a hybrid machine. The machine is to be designed to be able to manufacture optical, functionally integrated components or complete optical multi-material systems. In this case, laser polishing is considered as the post-processing method. Evaluation criteria are established for the various configurations of the hybrid machine, on the basis of which the selection of individual components of the hybrid machine can be justified. However, since these criteria are application-specific, no quantification of these criteria will be given. The result is various concepts for the integration of a laser polishing system into an additive manufacturing system with a focus on the manufacture of optical components.

2. HYBRID MANUFACTURING WITH LASER POLISHING

2.1 Hybrid processes

It is difficult to define hybrid manufacturing processes at the scientific level. A rough approach is "the combination of two manufacturing processes into one new process". However, this variant offers great freedom of interpretation. If one considers the classification of all manufacturing processes according to DIN 8580 [5], the following categories are available:

- primary forming
- transforming
- separation / subtractive manufacturing
- joining
- coating
- changing material properties

The question arises as to whether, for a hybrid manufacturing process, the processes involved must originate from different categories - such as original forms and forming - or whether subcategories must originate from original forms: Casting processes and additive manufacturing - are sufficient. [6]

Furthermore, the question can be asked whether both processes must be located in the same machine, or whether the component should be transferred to different machines and thus a sequential production takes place. A last point that can

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be considered is the type of energy input. Is a hybrid process characterized by the use of different forms of energy, such as electrical and mechanical energy, to process the material?

With these explanations it becomes obvious that the question of a fixed definition of hybrid manufacturing processes cannot be answered unequivocally. Therefore the following definition is proposed for this paper:

A hybrid manufacturing process is the combination of two processes from different categories of manufacturing processes according to DIN 8580. A combination of two processes of the same category is called a sub-hybrid. Both processes do not have to be integrated in the same machine.

For this work, an additive manufacturing machine (primary forming) and a laser polishing plant (transforming) are combined, which justifies the term of the hybrid manufacturing machine.

2.2 Laser polishing

The main advantage of laser polishing over other post-processing methods lies in its physical working principle: there is no subtractive machining, which means no contamination of the components or systems during production with contaminants, but a re-melting of the surface. In addition, no additional materials are used to machine the surfaces. Laser polishing is therefore more suitable for hybrid production of optical components than other post-process procedures.

Laser polishing can basically be applied in two variants. The surface is treated once with a laser in cw (continuous wave) mode and once in pulsed mode. In both variants, the surface is shaped in a predefined scanning pattern. In cw mode, the energy input melts the focus volume in order to completely melt partially fused particles, for example. This eliminates the need to clean the surface of unmelted material, as this is connected to the surface by polishing. At the same time, however, this also increases the geometric deviation of the component, since more material is processed than is required.[7,8,9]

To demonstrate the effects of laser polishing in cw mode on optically functional surfaces, figure 1 shows the comparison between a post-treated and a non-post-treated surface. A component can be seen which has been produced by selective laser melting. The requirement on the surface of the component is to achieve the highest possible reflectivity in order to be able to be used as a reflective optical component. The material used here is the aluminium alloy AlSi10Mg, whereby the component has not undergone any further processing. This means that the component has not been cleaned or other wisely changed in surface condition. This condition can also be found in the hybrid manufacturing process, as the surfaces to be polished cannot be cleaned or treated without removing the component from the machine. The figure shows that the treated surface is significantly more reflective and has no loose particles.

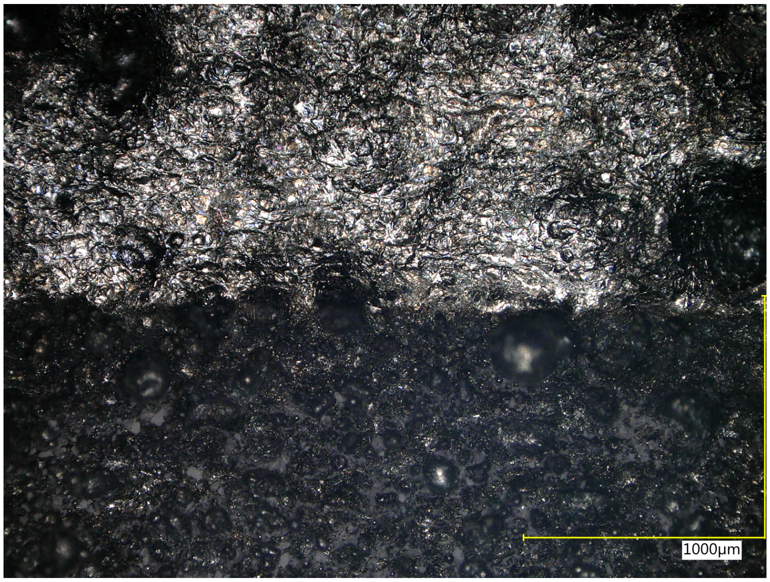

Figure 1: White light image of an additively manufactured aluminium sample; the upper half is polished with a CO_2 laser, the lower half is completely untreated.

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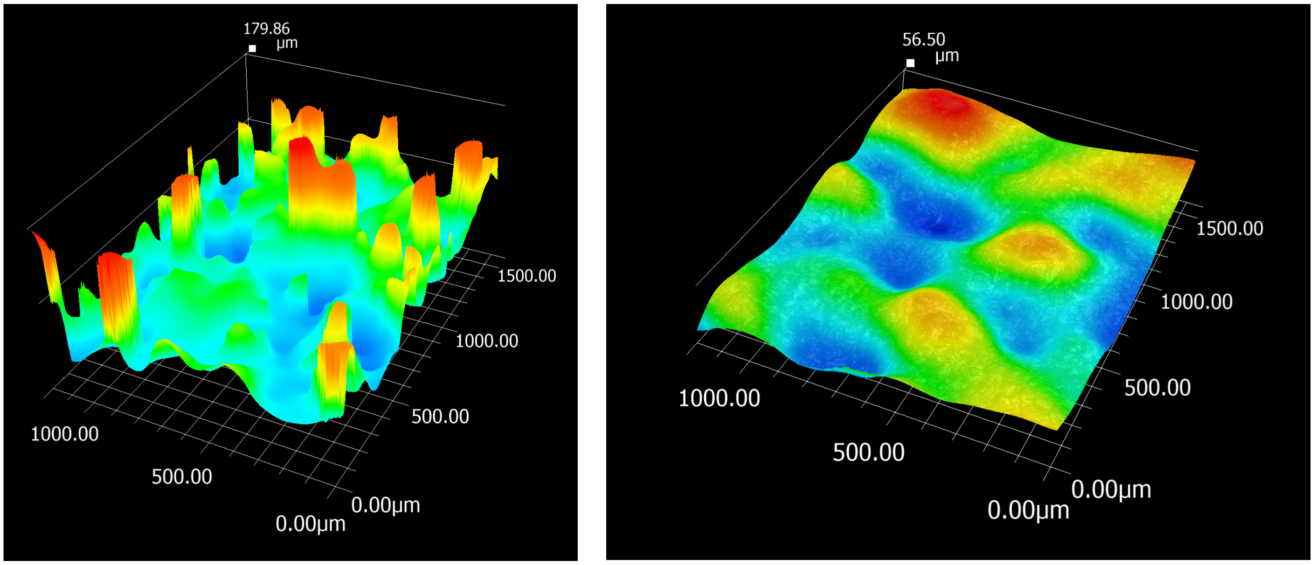

Figure 2: Surface finish of the AlSi10Mg sample; left) untreated surface, right) polished surface

Figure 2 shows the difference in the surface finish of the two surfaces. A comparison of the two surfaces shows that polishing creates smoother surfaces and the roughness values decrease significantly. Particles that were only partially melted during manufacturing are completely melted by laser polishing, which can improve the surface quality. In the untreated case there are elevations of up to 180 µm due to partially fused particles in the surface, after the laser treatment only of approx. 57 µm. The average roughness here is already in the single-digit µm range.

The polishing results shown here were achieved by five consecutive polishing iterations. The results can be improved with further iterations. However, physical limits are reached by the process if the surface is polished in such a way that the surface roughness is more strongly influenced by the scan pattern than by inhomogeneities with fused-on particles. The individual paths of the pattern can be measured, which lead to a residual roughness that in turn influences the optical quality of the reflective surface. From this point further iterations with polishing in cw mode do not lead to an improvement of the surface roughness, as this is created by the polishing process.

In order to avoid the problem of melt paths, polishing can also be carried out by using laser pulses, which cause only a small thermal input into the material. The laser pulses achieve high intensities in the focus volume, which in turn leads to non-linear optical effects. In this case this is laser ablation, whereby the energy input causes material to be 'explosively' separated from the component. Since this process can only take place in the focus volume, where sufficiently high intensities are achieved, polishing can be performed with very high resolution and very low ablation volumes. In addition, the interaction times between laser pulse and material are short enough that there is very little heat conduction and thus a small heat-affected zone, whereby the material is not melted.[10]

The polishing procedure now ensures that material is removed from the focus volume. Since the focus volume can be selected very small, roughnesses in the two-digit nanometer range can be achieved. This, however, contradicts the classification of laser polishing as a transforming post-processing method introduced at the beginning. However, the volume formed on the surface in cw operation is considerably larger than the material removed in pulsed operation. Under this aspect, laser polishing continues to be regarded as a forming process.

3. DEVELOPMENT OF CONCEPTS FOR A HYBRID MACHINE

In the following chapter, concepts for the hybrid manufacturing machine are developed. Various requirements are analyzed and the necessary components of the machine are listed. The various technological possibilities for implementation are structured in a morphological box, which is used to create various solution proposals for the machine. The monomaterial manufacturing of optical components is used as an exemplary setup.

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3.1 Requirements for the hybrid machine

In order to work out the requirements for the hybrid machine, various statements must be made for the manufacturing process. These statements have an influence on the choice of components for the additive manufacturing system as well as for the laser polishing system. This includes

- Material used
- Kinematic degrees of freedom (DOF)
- multi-material manufacturing

The processed materials are decisive for the design of the machine. The type of material feed and the laser sources to be used depend on these configurations. Figure 3 shows two absorption spectra for the materials AlSi10Mg and for silicate glass. Since the physical principle of manufacturing and post-processing is based on the melting of the material, laser sources with wavelengths that represent an absorption peak for the respective material should be used. However, when emphasis is placed on multi-material processing, it may be necessary to use multiple laser sources as a single source can cause inefficient melting processes.

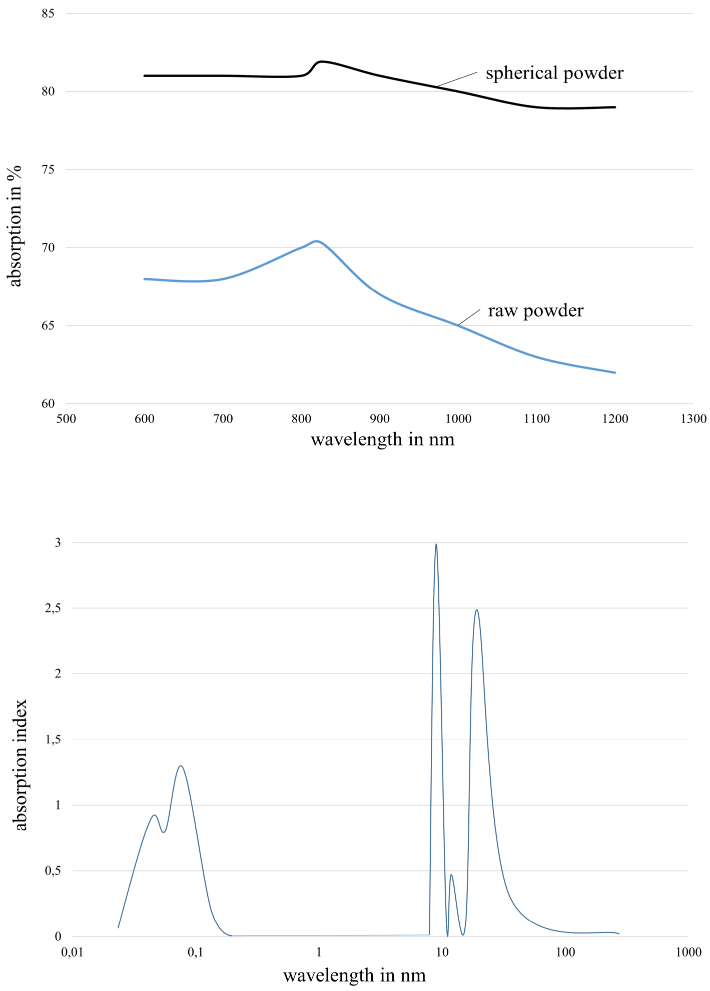

Figure 3: Absorption spectra for different materials; top) AlSi10Mg in different powder preparations according to [12], bottom) silicate glass according to [11]

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A further requirement is the number of kinematic degrees of freedom and their division into the individual subsystems of the production plant. The subsystems can be divided into the building platform, the laser system for additive manufacturing and for laser polishing. The degrees of freedom of the laser systems are decisive for the beam guidance. With a sufficient number of degrees of freedom, surfaces can be accessed for laser polishing. This is achieved by the relative positioning of the cavity or surface to be machined relative to the laser beam source, which can manifest itself either in the alignment of the component by the movement of the building platform or by a change in the direction of the polishing laser beam.

In addition, the degrees of freedom can also be used to ensure that the radiation always incides on the component surface perpendicularly. This has two advantages. On the one hand, it prevents the beam cross-section on the surface from increasing, thus reducing the energy input per surface element. On the other hand, it has been observed that surface inclinations of the component lead to different surface properties. Bevelled surfaces support the staircase effect, which has a decisive influence on the surface roughness. Thus, both the manufacturing process and the post-processing can be influenced by the number of kinematic degrees of freedom.

As soon as the three core statements shown have been dealt with, various requirements can be formulated for the production plant on the basis of these. These requirements include the laser power, the required building space, the optics required for beam guidance, the selection of protective gases or the installation of active extraction mechanisms during production. The requirements are not quantified in this paper because they are application-specific.

3.2 Morphological box for monomaterial manufacturing

In the following, a morphological box (table 1) will be created with the help of which various possible solutions for the integration of a laser polishing system for monomaterial manufacturing can be worked out. It is assumed that the laser polishing system can be used for both cw and pulsed polishing.

table 1: Morphological box for the integration of a laser polishing machine in monomaterial additive manufacturing (blue coloured cells represent one possible solution for a concept for the hybrid machine)

solution function	1	2	3	4	5	6
material	AlSi10Mg	Ti6Al4V	polymer	silicate glass	…	…
initial state	powder bed	powder + nozzle	filament + nozzle			
number of lasers	1	2				
laser additive manufacturing	CO_2	Nd:YAG	Ti:Sa	Yb-fiber	GaAlAs diode	UV
laser polishing	CO_2	Nd:YAG	Ti:Sa	Yb-fiber	GaAlAs diode	UV
beam guidance additive manufacturing	scanning mirrors (2 DOF)	fibre + robotic arm (6 DOF)	fibre + 3-axis stage (3 DOF)	fibre + 5-axis stage (5 DOF)		
beam guidance laser polishing	scanning mirrors (2 DOF)	fibre + robotic arm (6 DOF)	fibre + 3-axis stage (3 DOF)	fibre + 5-axis stage (5 DOF)		
setup bulding platform	static (0 DOF)	3-axis stage (3 DOF)	5-axis stage (3 DOF)	hexapod (6 DOF)	robotic arm (6 DOF)	

In order to find a solution path for the hybrid system, the system requirements must now be included. However, as these vary from case to case, it is not possible to find the best solution. In addition, not all paths make sense arbitrarily, as some solution options are mutually exclusive.

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In order to be able to make statements about the performance of different combinations, different solution options can be qualitatively assessed. The criteria by which an evaluation can be made include, among other things:

- Number of total kinematic degrees of freedom
- Dynamics of the subsystems
- position repeatability
- autonomy
- expenses
- maintenance cost

As an example, a cost-effective variant with as many degrees of freedom as possible for the processing of AlSi10Mg in the selective laser beam melting process is to be developed. Thus the material is determined and it is also certain that it is a powder bed-based process. With the help of the listed evaluation criteria it becomes clear that the use of two laser beam sources is excluded, since this would at least increase the expenses. Thus the polishing is carried out with the same laser as the production. Using the absorption spectrum of AlSi10Mg, the choice for the laser is a Yb-fibre laser. The two operating modes of the laser polishing, however, require two optical paths that can be used for cw mode and pulse mode. For the beam guidance (fibre-guided) and for the construction platform, a 5-axis stage is used. This means that both the component and the laser beam source can be positioned in such a way that perpendicular irradiation of the component surface is possible.

4. DISCUSSION

The morphological box shown serves for the development of concepts for the integration of a laser polishing system into an additive manufacturing system. The results demonstrate the combination of the individual system components and indicate several solution proposals for the realization of the hybrid machine. However, it must be noted that these are concepts that do not describe the structure of the individual components in detail. For example, it is not made clear which mechanisms can be used for pulse generation for laser polishing, or how the changeover from cw operation to pulse operation can take place. These questions can often only be answered as soon as the theoretical framework of the entire system is available.

The morphological box must be extended in order to be able to implement the possibility of multimaterial production in a hybrid manufacturing machine. Thus it is now possible to include other additive manufacturing processes such as fused deposition modelling, which can apply thermoplastics to the building platform via a nozzle. In principle, the different material classes that can be used for additive manufacturing mean that there is hardly any possibility of achieving firmly bonded connections. One must consider form-fit connections, which are again challenging in design, but also place greater demands on the degrees of freedom of the system, since the materials must be applied for example in cavities, in order to provide a connection. In addition, a laser source is required which can process different material classes for laser polishing, both in cw and pulsed mode.

It quickly becomes clear that with the increasing number of materials to be processed, the complexity of the hybrid machine also increases. Particular attention must be paid to the interaction between the laser beam source and the material used. Thus, it may be possible for one laser beam source to process several materials and thus reduce the number of laser beam sources required. It is also possible to equip the laser polishing machine with only one laser beam source. A CO_2 laser that can process glass, polymers as well as metals, albeit with different efficiencies, is one possibility for this purpose.

As an example, a machine will be designed which will produce glass lenses including optomechanics (e.g. the lens mount). The main criterion is the quality of the optical component. Thus, the material classes are fixed and the corresponding manufacturing processes can be selected. Even if the additive manufacturing of glass requires further research, it is assumed that the glass is present as a fibre and is processed by laser deposition welding. The suitable laser

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source according to the absorption spectrum is a CO_2 laser. Either aerosols or polymer filaments can be processed for polymer manufacturing. If the process duration is an evaluation criterion, a fused deposition modelling system should be used, as the material can be processed more quickly compared to other additive manufacturing processes. In addition, no laser is required. Aerosol jet printing, which is carried out with a UV laser, ensures higher accuracies. A CO_2 laser is also used for laser polishing, which is already used for glass processing and can also process polymers. Since the highest possible quality of the components is required, the highest number of degrees of freedom is chosen for each beam guidance setup, as this ensures that the components are always correctly aligned with the laser beam.

The morphological box does not take into account the way to change between the individual manufacturing processes. Depending on the combination, this can be selected differently and may be very special for the respective application. Also the control of the individual components of the production line cannot be determined at this point.

In addition, further core aspects of additive manufacturing and current research are included in the consideration of the hybrid plant, which can be left out for the first considerations of the concepts. This includes

- Quality assurance through optical measuring methods and simultaneous adaptive adjustment of process parameters
- Active extraction in processes that cause contaminations by loose particles
- Adjustment of the energy input during a melting process
- Positioning and exchange of different print heads in the installation space
- Dimension of the machine
- Inert gases
- Building space and building platform temperatures

These aspects must be taken into account in the design of the installation, but can only be considered once the concept of the installation has been established. This shows the relevance of the concepts for the hybrid manufacturing machine. The quality of the concepts depends mainly on the completeness of the morphological box and the associated knowledge of the individual components of the hybrid machine. An extension of the box is always possible.

An additional challenge is the setting up of requirements for the machine and its components. Particularly for new materials for additive manufacturing, investigations must be carried out with regard to their optical properties, such as the absorption behaviour in the initial state and in the processed state.

5. CONCLUSION

In this work, morphological boxes are used to develop concepts for hybrid manufacturing machines. First, the advantages of laser polishing and its areas of application are presented in order to make clear that this post-processing method is particularly suitable for optical components. With the described requirements, selection options for the system can be worked out, which are subdivided into a morphological box and combined into an overall solution or concept. Special requirements such as laser power or building space cannot be dealt with, since these are application-specific and therefore have no influence on a general approach.

For the cases of monomaterial and multimaterial manufacturing, two examples are presented and described with the help of morphological boxes. In order to create solutions, it is noticeable that evaluation criteria are necessary with which application-oriented solutions can be identified. At the same time, missing aspects of the solution spaces were discussed, which cannot yet be included in the considerations due to the necessary machine concept.

In summary, it can be stated that a transparent and comprehensive method is used with the help of the morphological boxes, which enables the creation of concepts for hybrid additive manufacturing machines. However, this also requires a strong background knowledge of the materials and processes used and can therefore be demanding.

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