Fraunhofer
IAPT

Fraunhofer Research Institution
for Additive Manufacturing
Technologies IAPT

Hybrid additive manufacturing

Alliance Deep Dive | 2022

exclusive

ADDITIVE
ALLIANCE

Contact

Fraunhofer Research Institution for
Additive Manufacturing Technologies IAPT

Am Schleusengraben 14
21029 Hamburg-Bergedorf
Germany

+49 40 48 40 10-500

info@iapt.fraunhofer.de

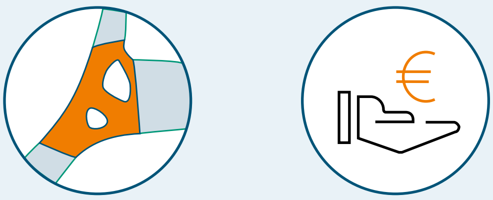
www.iapt.fraunhofer.de

www.linkedin.com/company/fraunhofer-iapt

www.youtube.com/FraunhoferIAPT

1. Abstract

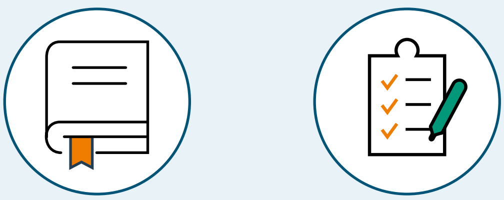
Motivation



Hybrid additive manufacturing to ...

… save costs and resources during printing
… enable production of bigger parts
… avoid accessibility restrictions
… reduce the complexity of parts

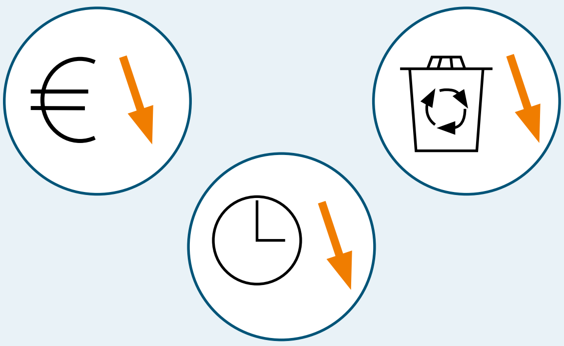
Approach



Hybrid manufacturing guide

- Identification of cost-saving potential
- Identification of a suitable technology
- Checklists for a tailored hybrid

Results



Savings potential

- Reduction of costs
- Reduction of material waste
- Reduction of production time
- Possibility of new products

2. Content

1. Abstract **4**

2. Content **5**

3. Acknowledgement **6**

4. About the authors **7**

5. Motivation **8**

6. Approach of the Deep Dive **10**
- 6.1 Definition of hybrid additive manufacturing 11
- 6.1.1 Combination of different production technologies 11
- 6.1.2 Combination of different materials 13
- 6.1.3 Combination of separately manufactured individual parts 14

7. Characteristics of hybrid additive manufacturing **16**
- 7.1 Joining individual components 16
- 7.2 Printing on existing components 24

8. Hybrid additive manufacturing guide **26**
- 8.1 Identification of cost-saving potentials with hybrid AM 27
- 8.2 Identification of a suitable hybrid AM approach 30

9. Use case demonstration **34**
- 9.1 Joining of additive manufacturing and conventional parts 35
- 9.2 Printing on conventional parts with Powder Bed Fusion 37
- 9.3 Printing on conventional parts with Directed Energy Deposition 39

10. Summary & Conclusion **42**

11. References **44**

12. Imprint **47**

3. Acknowledgement

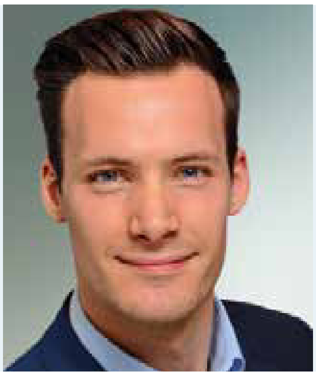
Deep Dives are reports intended exclusively for the members of the Additive Alliance®. They provide the latest insights into the science behind additive manufacturing (AM). We extend our profound thanks to the members listed below. This Deep Dive could not have been created without their financial support.

Mesago Messe Frankfurt, the organizer of Formnext, has been the official sponsor and cooperation partner of the Additive Alliance® and Fraunhofer IAPT since 2020.

4. About the authors

The authors of this Deep Dive demonstrate the possibilities of reducing the comparatively high costs of printing components through new manufacturing concepts. In this study, the focus is not on optimizing the actual printing process, but on combining different manufacturing approaches to realize further business cases that would otherwise fall short due to economical or technical limitations. This hybrid additive manufacturing approach is analyzed and presented in this Deep Dive by a team of experts from different printing processes as well as by colleagues with extensive industrial experience. Furthermore, the authors are leading various research projects aimed at developing hybrid AM components or at qualifying their application-specific suitability for such an hybrid approach.

Dipl.-Ing. Markus Lingner



Markus Heilemann, M.Sc.

Contact

Markus Heilemann, M.Sc.
Head of DED Team
Telephone +49 40 48 40 10-627
markus.heilemann@iapt.fraunhofer.de
www.iapt.fraunhofer.de

Hannes Zapf, M.Sc.
Robert Lau, M.Sc.
Dipl.-Ing. Frank Beckmann

5. Motivation

The production of 3D-printed components can be limited by various factors. Potential use-cases often stall due to the high costs of 3D printing. However, other factors such as the size of the printing chamber, the complexity and the dimensions of the component can also be limiting factors.

One approach to address this problem is to only print sections of the component and join them with conventionally manufactured semi-finished products. Since printing costs are largely determined by component volume and not by its complexity, costs can be saved as a direct result.
The diagram below (Figure 1) demonstrates the potential of this design approach in mitigating the above-mentioned limitations in 3D printing. For conventionally manufactured components, unit costs typically increase with growing geometric complexity. For printed components, an increase in component complexity typically does not lead to an increase in manufacturing costs, which, however, are generally at a higher level. A high potential for saving manufacturing costs for the final component can be achieved if hybrid manufacturing is used in this way to produce a final component from both simple geometric semi-finished parts and geometrically complex printed structures.

Insights to be gained in the Deep Dive:

1) A clear understanding of possible hybrid approaches in additive manufacturing

2) Concepts for designing parts using hybrid additive manufacturing and when to apply them profitably

3) A reference guide for identifying potential applications of hybrid AM based on cost-saving potentials

Hybrid manufacturing can have many advantages

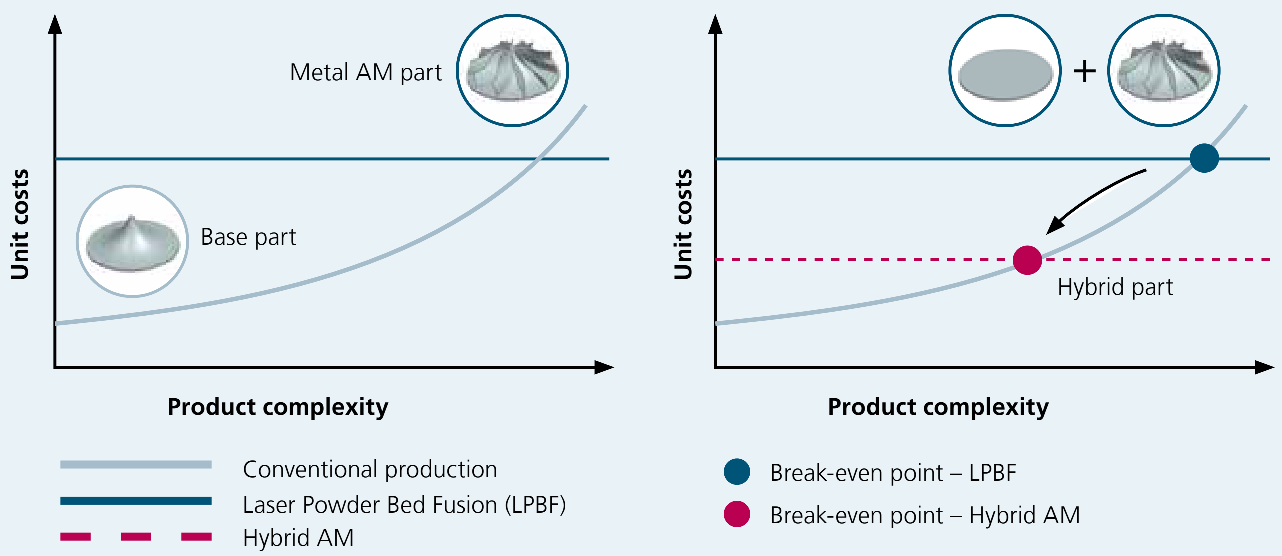


Figure 1: Comparison of the break-even point in additive manufacturing (AM) and hybrid additive manufacturing, whereby component costs can be reduced by substituting a defined volume of AM with a semi-finished product

Figure 2: The Deep Dive offers a better understanding of possible hybrid approaches in additive manufacturing

»By combining material deposition and machining in one machine, functions can be integrated in a way that was not possible before.«

Figure 3: Analysis of a multi-material heat sink, a component printed from two different materials (copper and stainless steel)

6. Approach of the Deep Dive

6.1 Definition of hybrid additive manufacturing (hybrid AM)

In the context of 3D-printed components, the term »hybrid« is used in more than one circumstance. Three different scenarios in which one might speak of »hybrid« in 3D printing are outlined below. For differentiation and clarification, the first two hybrid scenarios are only briefly explained before the focus and direction of this report is aimed at the third scenario presented in Chapter 6.1.3.

6.1.1 Definition 1 – Combination of different production technologies in one machine

In terms of the manufacturing technology used, a process chain is called hybrid if at least two different manufacturing processes are employed in one machine [Sef22]. For example, a component manufactured by Powder Bed Fusion (PBF) is called a hybrid part, only if the printing and subsequent milling of functional surfaces are performed in one machine.

While the market for hybrid machines for the LPBF process is rather limited, there are many suppliers of hybrid machines using Directed Energy Deposition (DED). The reason for this is that the DED process is a near-net shape manufacturing process that requires mandatory machining of all surfaces, not only the functional ones.

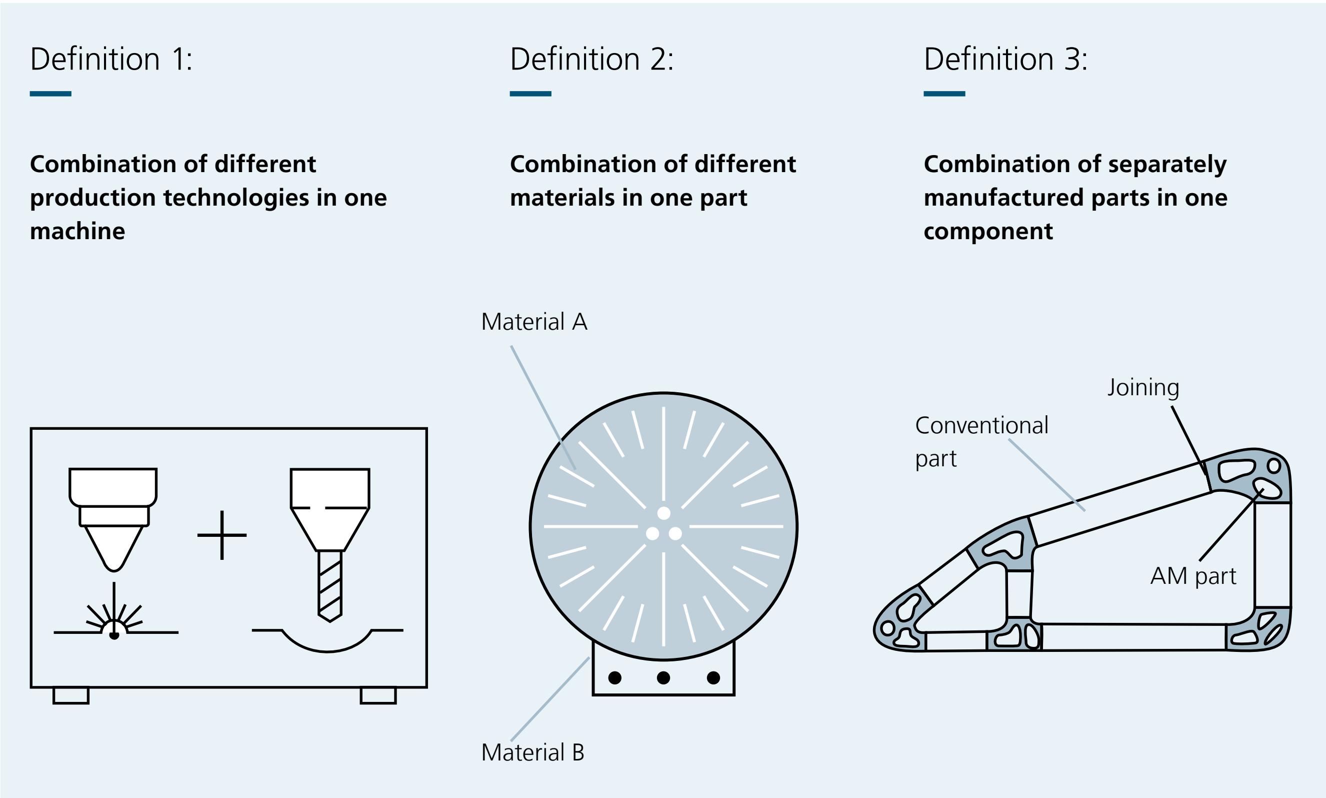


Figure 4: Different definitions for hybrid additive manufacturing

Figure 5/6: Two processes are combined in one machine to print a net-shape geometry using laser powder deposition and a milling process (either in between or at the end) to machine the part to the final contour [Dmg22]

Different production technologies in one machine open new ways for automating the entire process

Several machine tool manufacturers have added a deposition head to their standard milling machines. In some cases, this head is integrated into the tool magazine to enable automatic tool exchange in the spindle. Meanwhile, there are several different deposition heads available for integration into standard milling machines. These hybrid add-ons are designed so that they can be purchased and integrated independently [Wri22]. In this case, the deposition head is then inserted into the spindle instead of a milling tool and automatically connected to a supply unit.

The disadvantages of using such hybrid machines include the comparatively low degree of utilization of the installed equipment. Depending on the process used (additive or subtractive), the periphery of the respective other process cannot be used. For instance, the laser utilization rate during the subtractive process is zero. Other disadvantages include the integration of safety precautions required for the additive process in a subtractive machine. This ultimately increases the overall cost of the machine.
However, the advantage is a significant reduction in production lead time and overall costs. This is because the machine set-up times between additive and subtractive processes, which are normally required for conventional processes with separate machines, are eliminated.

Figure 7: Automated tool change system of a milling machine for a laser metal deposition process head including its supply unit [Hyb22]

Figure 8: Layer-by-layer milling of the component contour in the LPBF process with an integrated milling head [Mat22]

Figure 9: Multi-material heat sink developed by Fraunhofer IAPT and 3D printed at Aerosint S.A. with a copper kernel and stainless steel shell

6.1.2 Definition 2 – Combination of different materials
Another approach to hybrid manufacturing is the production of components in which different materials with very diverse properties (such as corrosion resistance, toughness, strength, thermal conductivity, etc.) are merged together in a single product. These multi-material applications have long been used in DED processes, especially for coating components with special material to achieve surface properties such as wear resistance or corrosion resistance.

This approach is being extended to the application of additive manufacturing, where certain structures receive functional surfaces. With powder-based DED processes different material gradients can be achieved within a component. These material gradients can also be changed during the process. Depending on the material pairing, one of the greatest challenges in multi-material processing are cracks that tend to occur in the material transition zone due to brittle phases. This phenomenon can be caused by the mixing of the different materials or by the different thermal expansions [Tah17].
In addition, there are also approaches to transfer this to wire-based DED systems – essentially with two different objectives. One is to produce alloys that are not available or feasible to produce in wire form by in-situ process alloying. Several publications address the production of titanium aluminides [Hen19] relies on a MIG process plus hot wire, whereas [She19; Wan18; Yan20] uses the TIG process to produce the desired γ-TiAl by feeding two hot single wires of titanium or aluminum.

Secondly, this approach is chosen to achieve graded properties in the component. Examples are the combination of FeNi36 and Mn4Ni1.5CrMo steels [Lei20; Tre19], Steel SS231 and Inconel 625 [Kum21] or the combination of the aluminum alloys 6060 and 5087 [Hau21]. DED multi-material is therefore no longer limited to powder-based processes.

Two discrete components become a final product

In LPBF applications, there are several efforts to produce multi-material graded components in one process step. However, the challenge lies in the powder bed. Here, the unused powder at the end of the process is of an unknown mixing ratio of two materials and therefore cannot be reused. At the industrial level, a recoating process has been developed that can produce multi-material components using the LPBF process [Aer 22].
In the process of recoating a new powder layer, the required material is applied in a spatially resolved manner and then exposed using the familiar method with a laser scanner. This allows, for example, to produce heat exchangers in a special design. It combines the high-strength and corrosion-resistant properties of stainless steel for stability with the good thermal conductivity of copper (Figure 8).

Another approach has been developed through research whereby one of the two powders is magnetic. It can thus be separated and recycled after multi-material printing [Fra 20b].

6.1.3 Definition 3 – Combination of separately manufactured individual parts

Called hybrid production, a different approach is pursued using a process that has become well established in the recent past. Hybrid AM components are manufactured by joining a 3D-printed structure with a conventional semi-finished product. This can be done either during the printing process, by printing directly onto a semi-finished product, or after the printing process, by joining the printed component to the semi-finished product (e.g. through welding, soldering or bonding).

The main motivation for using this technique is primarily driven by manufacturing costs or component size. Wherever it is necessary to produce a complex or individual component, this is printed. Wherever it is technically feasible to integrate standard semi-finished products into the component, then they are designed so. The expensive printing process is thus only used where it is necessary. The design freedom of the printing process offers additional potential for optimizing the entire

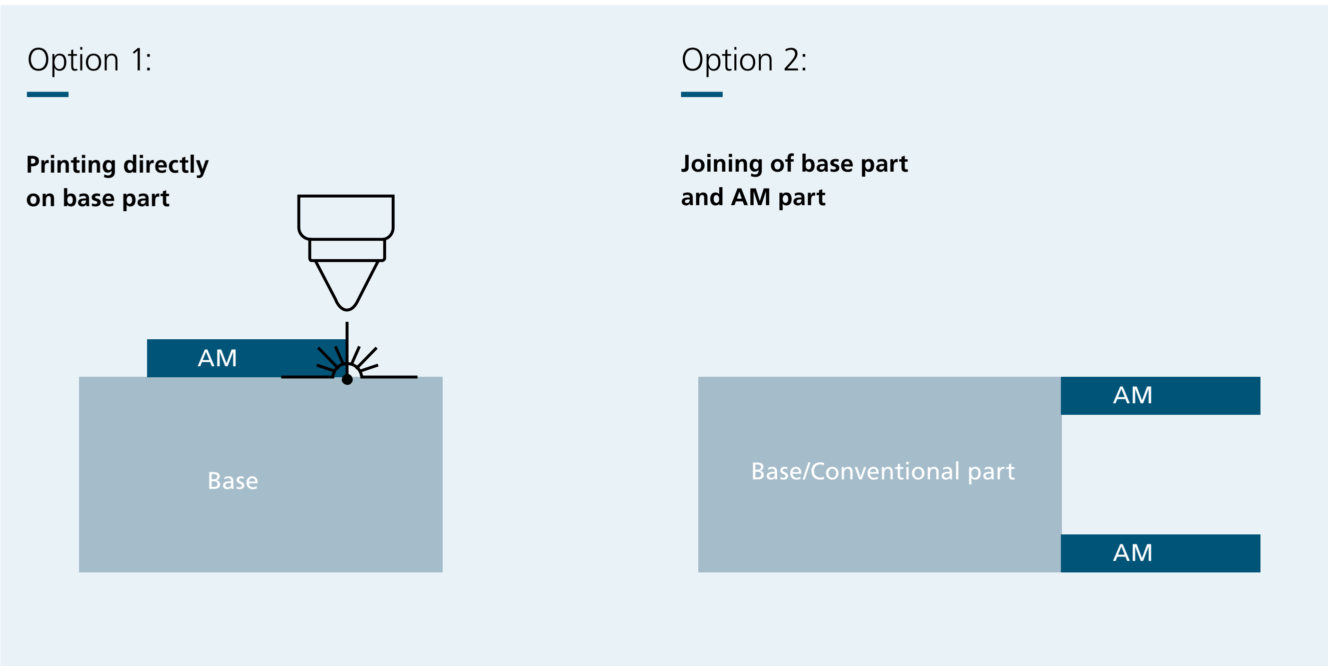


Figure 10: Two different concepts for combining a printed part with a standard base structure

»Our four main motivation criteria for hybrid AM are cost, size, complexity and accessibility.«

Figure 11: Hybrid car body structure, built with printed connecting nodes and extruded profiles [Eda22]

process chain. For example, the printed area can be optimized for lightweight construction or with complex internal cooling channels for better heat dissipation.
In addition to the costs, component size is also driving this hybrid approach. If a component cannot be manufactured in one piece, for example using a PBF machine, it is divided into smaller parts and then joined together. Due to the generally larger build area associated with DED processes, it is not the component size but the accessibility of the print head or the complexity of the component that necessitates a hybrid design. As discussed above, the term »hybrid additive manufacturing« can therefore be used to describe different approaches However, this study and the following chapters of this report focus exclusively on the hybrid approach of manufacturing components by combining several parts, with at least one additively manufactured part.

7. Characteristics of hybrid additive manufacturing

7.1 Joining individual components

The various possibilities for producing such a hybrid component are described in more detail below. Also, the technological constraints to be considered in the design of the components are explained.
In the production of hybrid components, a printed part and a semi-finished product must be joined together. The joining processes specified in DIN 8580 are used for this purpose. In addition to cold joining processes such as gluing or riveting, hot joining processes are also used, predominantly welding processes in the metal sector.

The following chapters concentrate on the welding processes, as the objective of this study is to identify hybrid applications for metal components joined with material bonding. Furthermore, most of the metal 3D printing processes are also a welding process in the original sense. The choice of the appropriate joining method for the hybrid process depends largely on the application. Factors such as material, joining zone, material thicknesses, etc. influence the welding process.

Design criteria for selected welding processes

	Laser beam	Electric arc	Electron beam
Low investment costs	poor	good	poor
Filigree weld seams possible	good	neutral	good
Low thermal distortion	good	poor	good
High welding depth/penetration	good	poor	good
High gap bridging	poor	good	poor
High welding velocities	good	poor	good
Low welding environment requirements	poor	good	poor
Low safety requirements	poor	good	poor
Low welding preparation requirements	poor	good	poor

- good
- neutral
- poor

Table 1: Comparison of the advantages and disadvantages of different welding technologies for a hybrid manufacturing approach

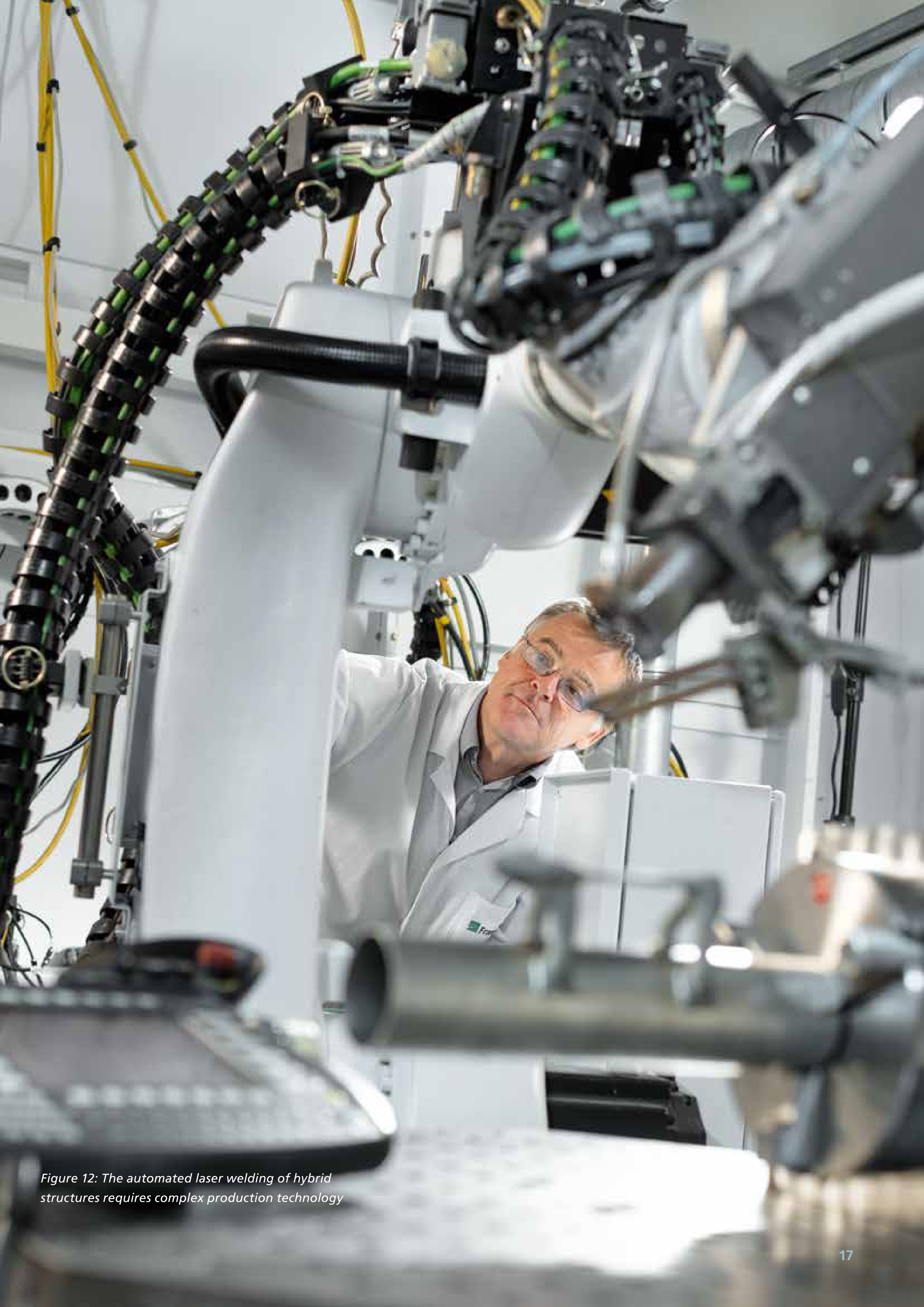


Figure 12: The automated laser welding of hybrid structures requires complex production technology

Welding of printed materials is sometimes a real challenge

In 3D printing application, laser welding processes are predominantly used to combine complex and/or filigree components. Other commonly utilized welding processes are compared in Table 1 (page 16) with their respective advantages and disadvantages. In addition to the choice of welding process, further parameters must be considered when designing hybrid components. The following is an overview of material pairing, microstructure, heat treatment and joining zone design.

Material pairing
Material pairing has a major influence on the design of the hybrid process chain. The combination possibilities of the available alloys for the additive and conventional processes are very high. For this reason, an overall consideration of welding suitability is very complex and depends on very individual factors.

Table 2 (page 19) gives an overview of relevant standards which, depending on the material group, can be used for the qualification of different welding processes as well as for the evaluation of welding results. Several research studies have been carried out on the welding of hybrid components.
The selection of publications on the individual material groups depicted in Table 2 can be used for a detailed consideration.

One particularity revealed through research is the welding of aluminum alloys to a printed part. Here, identical alloys show different behavior in the welding process depending on the manufacturing process.

The example shown in Figure 13 illustrates the challenge of welding AlSi12 aluminum alloy. The illustration on the right of Figure 13 illustrates how AlSi12 (printed with LPBF) is joined to a conventional cast AlSi12 plate by laser welding. There is a distinct difference visible in the weld seam and especially in the pore formation for the different component combinations. According to Beckmann [Bec17], this phenomenon is significantly influenced by to the powder used as well as by its age and by the moisture in the 3D printing process.

Microstructure and weld seam properties
The application of a weld seam always constitutes a local heat exposure for the material to be welded. In most cases this has negative effects on the microstructure. Especially in the case of laser-/electron-beam processes, the higher energy densities compared to arc processes lead to higher cooling rates and thus to greater hardening effect or increased residual stresses within the weld seam.

Laser beam welding of AlSi12 for different material configurations

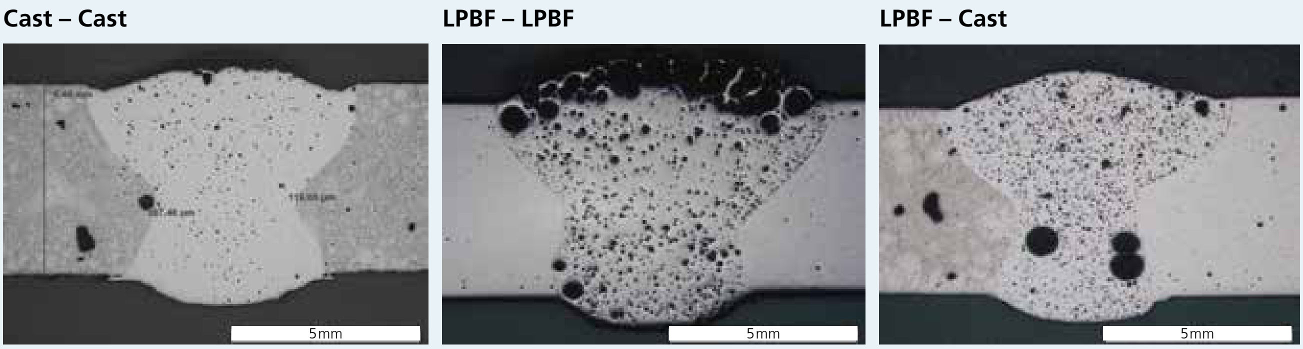


Figure 13: Butt joints of AlSi12 with identical process parameters [Bec17]

Overview of same material pairings

Al-alloys	St-alloys	Ni-alloys	Ti-alloys	
ISO 15607 Specification and qualification of welding procedures for metallic materials				Standards
ISO 15614-5 Arc and gas welding of Al – Welding procedure test	**ISO 15614-1** Arc and gas welding of St, Ni – Welding procedure test		**ISO 15614-5** Arc and gas welding of Ti, Zi – Welding procedure test	Standards
ISO 10042 Fusion-welded joints in Al-Quality levels for imperfections	**ISO 5817** Fusion-welded joints in St, Ni and Ti (beam welding excluded) – Quality levels for imperfections			Standards
ISO 13919-2 Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections for Al, Mg	**ISO 13919-1** Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections for St, Ni, Ti			Standards
Bec17, Bec15, Bif19, Dim22, Mic21, Möl20, Sch21	Akb19, Cai21, Haw22, Jae19, Mat16, Mok21, Sch19, Yan19, Zap20	Gei22, Jok19	Tav18, Wit15	Literature

Table 2: Overview of material pairings – Welding-specific standards and literature references for joining hybrid AM components

The correct design of the joining zone has a significiant influence on component quality and manufacturing costs

Generally, these effects generally lead to deterioration of the material properties and load-bearing behaviour. However, this can be minimised by appropriate process control during welding or partially corrected by heat treatment after the welding (see the following section on heat treatment). Alternatively, too rapid cooling can also be prevented by appropriate preheating of the material. In addition to the occurrence of residual stresses, the heat input can also lead to severe component distortion, depending on the process and component volume. Warpage and residual stresses are usually indirectly proportional. In the case of arc-based processes, the distortion is usually higher, but the remaining residual stresses are lower than in beam processes and vice versa.

While from a material strength point of view, weld seams are rather to be avoided, design-wise they allow an extension of the component variety and size. Joining a printed and a standard part by welding results in a hybrid component.

Heat treatment before or after welding
In most cases, AM structures must be heat treated after the printing process together with the build platform in order to reduce the thermal stresses that occurred during the printing process. The component can then be separated from the build platform and, for example, be finished mechanically.

If these parts are then welded to other parts in terms of a hybrid component, the welding process and the formation of a weld seam can lead to the negative metallurgical and

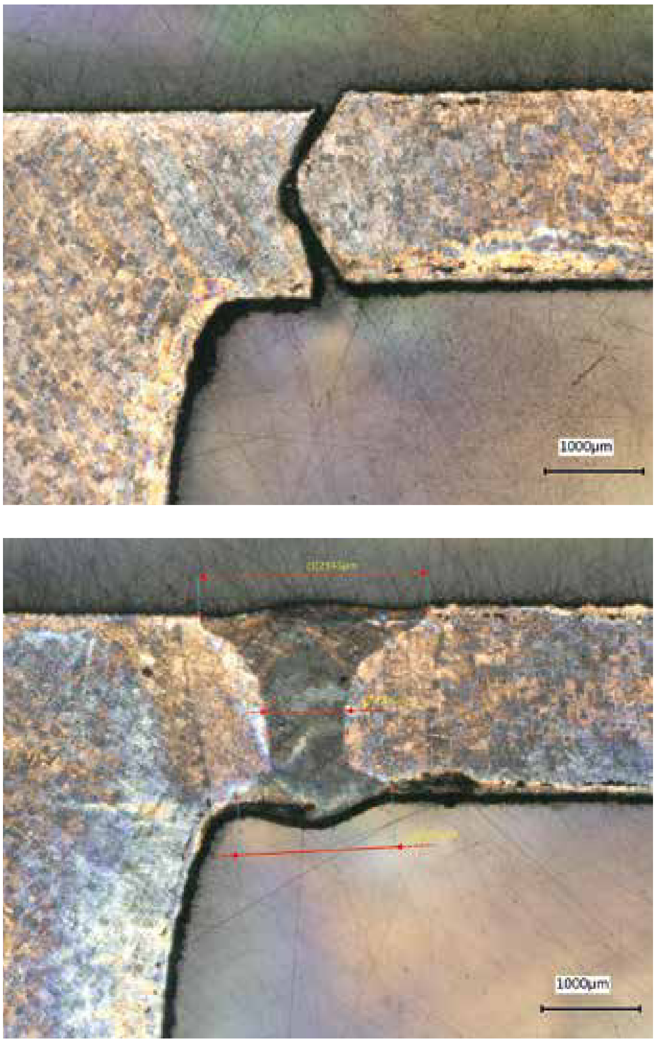


Figure 14: Printed joint zone preparation with positioning aid through prismatic joint gap

mechanical effects described above. These effects must there-fore be considered in the design of the component and when selecting the welding process. If necessary, heat treatment must therefore be planned again after welding, which can compensate for the negative effects to a large extent.

The feasibility and necessity of a heat treatment depends on several factors, e.g. material, component shape or wall thickness. The temperature and duration of the heat treatment also depend on the material and the application. Corresponding information is available in the appropriate material specifications, e.g. standards, technical specifications or material data sheets. If heat treatment processes are listed within the scope of process or component qualification, e.g. according to DIN EN ISO 15614, they must also be carried out accordingly on the hybrid components.

Design of the joining zone
An in-depth design and analysis of the joining zone can facilitate the positioning and alignment of the parts to be joined and, in individual cases, also prevent the molten material from escaping the joining zone.

The freedom of design in additive manufacturing offers new possibilities for joining zone design that would only be possible with great effort in conventional semi-finished products. For example, a geometry for a snap-fit or bayonet connection can be provided on the printed component, with the geometrically simpler counterpart being integrated on the conventional semi-finished product.

In this way, the effort required for the clamping mechanism can be reduced. Also, the interference collision contours caused by the clamping devices can be reduced, in some cases significantly. Figure 14 shows another sample of a joining zone design using a printed prismatic shaped geometry to orient the parts to each other. Table 2 summarises different joining design options depending on the geometric design of the hybrid component.

Using the geometric freedom to simplify the entire joining process
Table 3 does not provide a ready-made solution for hybrid joints, but illustrates various technical options for using the geometric freedom of the printed parts to simplify the entire joining process.
There is potential for optimisation, for example, regarding the positioning of the parts, the attachment of the parts for welding, the integration of clamping surfaces or the adaptation of different component cross-sections.

The described parameters are intended to provide starting points for the design of the weld seam of a hybrid component. If a hybrid component is to be developed for cost reasons, the relevant factors must be considered, e.g. any additional heat treatment and further steps in the joining process. Depending on the material and application, there are further specific issues that must be taken into account.

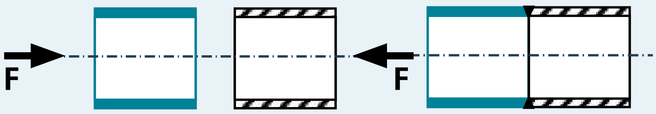
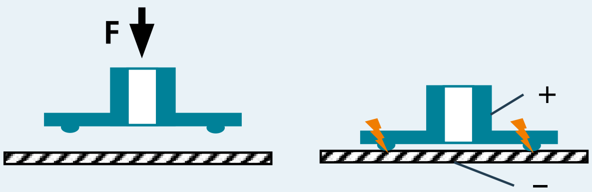
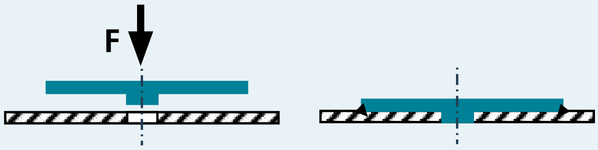
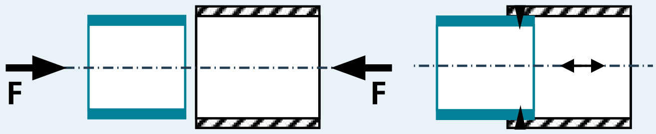
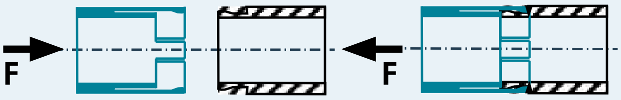
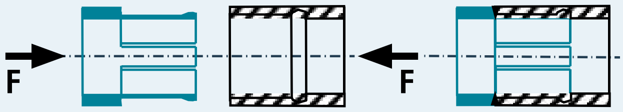
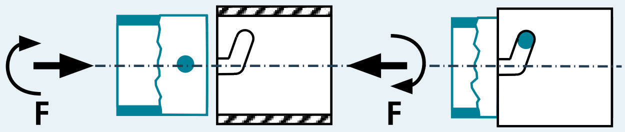
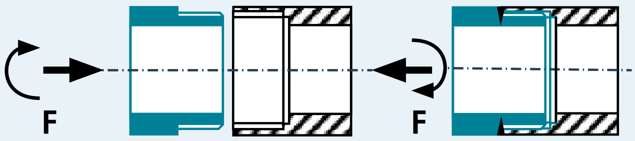
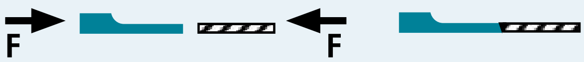
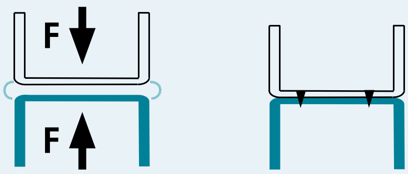
Joining zone design	Principle design	Advantages	Disadvantages
Butt joint		■ Simple geometry, easy to produce ■ No complex machining for the joining area needed	■ No centering aids ■ Complex clamping mechanism required for welding/centering
Overlap		■ Simple geometry, easy to produce	■ No positioning aids in the joining zone ■ Small joining cross-section for large material thickness
Printed welding humps		■ Welding humps can be simply printed as well	■ No media-tight connection
Printed centering pin		■ Easy positioning of the joining parts relative to each other	■ The printed positioning pin does not allow »high precision« positioning
Sliding sleeve (as special form for an overlap connection)		■ Axial tolerance compensation possible during joining	■ Sophisticated clamping technology to adjust the requested axial length
Outside snap		■ Function integration: positioning and clamping ■ Smooth inner wall after welding	■ Spring tongues visible after welding

Table 3: Design concepts for the joining zone

Joining zone design	Principle design	Advantages	Disadvantages
Inside snap		■ Function integration: positioning and clamping	■ No »smooth« inner wall after welding
Bayonet		■ Function integration: positioning and clamping ■ Defined rotational orientation of the parts to each other	■ Complex mechanical preparation of the conventional joining parts ■ Higher effort for automated pre-weld part assembly
Butt joint with integrated V-groove		■ Positioning aid integrated in the joining zone	■ Accurate mechanical preparation of the conventional joining partner necessary
»Printed« thread		■ Thread can be used for positioning and fixing ■ Component can already be mounted prior to connection by welding ■ Low quality requirements for the thread because it is not longer used after welding	■ Both joining partners must be provided with a thread ■ No rotational orien-tation via printed geometries ■ Complex joining process by rotary and linear movement
Butt joint with diffe-rent material thickness		■ low weld penetration requires ■ low laser power required ■ High welding speed possible	■ No centring aids ■ Complex clamping technology required for welding/centring
Positioning aids printed along with the pro-duct, which are later removed		■ Easily removeable positioning aids ■ Simple clamping mechanism	Additional effort to remove the positioning aids after welding

7.2 Printing on existing components

This specific process for producing a hybrid component involves printing the respective part directly onto a standard semi-finished product, which is also used as a substrate. The joining process after printing, described in section 6.1.3, is therefore not required, as the connection to the base body is integrated into the printing process. For this purpose, DED and LPBF processes are mainly used as additive technologies today. The use of binder jetting technology, for example, is not possible here. This is because this process explicitly prohibits a fixed connection to the substrate to ensure that the parts can shrink unimpeded during the debinding and subsequent sintering. However, this does not exclude the previously described approach of subsequent bonding with other semi-finished products.
Since the printed structure is »deposited« directly onto a base body, a full-surface connection of the material can be realized in the joining plane, something that is not possible with a subsequent welding of material with a large cross section. The full-surface connection can be advantageous with regard to increased strength requirements or sealing against any medium. Further characteristics of this hybrid approach are explained below.

Design of the parting plane
Depending on the additive process (DED or PBF), the design options for the parting plane between the printed and non-printed sections vary greatly. In the case of PBF, this should always be a flat surface that is parallel to the exposure plane of the machine and feature a high surface quality. In the DED processes, on the other hand, a freeform surface can also be used as the parting plane. The degree of complexity of the parting plane depends on the number of degrees of

Figure 15: The additive processes are qualified by means of a variety of elementary geometries

freedom of the DED handling system and the system's accessibility. For 3-axis CNC systems, the parting plane should be planar, since the machining head cannot be tilted to the base plate. Should the parting plane be composed of more than one parting plane at an angle to each other, the base plate must also be clamped. With 5-axis CNC systems, these restrictions can be avoided and, for example, the entire surface of a rotationally symmetrical base plate can be defined as the parting plane. A 6-axis robotic system with additional turn/tilt positioner offers the highest degree of flexibility, as both the robotic head and the base plate can be moved.

Clamping, positioning and measuring technology

For DED processes, the clamping tools for the base of the hybrid component is usually only limited by accessibility and, in case of closed DED systems, possibly the process chamber. Otherwise, standard clamping concepts are to be followed. Since the deposition of material to the base geometry is still a thermal joining process, the design must account for stresses etc.

The calibration can basically be carried out in two ways. Firstly, the semi-finished product is measured with the clamping tool using a defined base with the DED tool, which serves as the point of origin for positioning the DED structure. Alternatively, a point cloud of the semi-finished product can be achieved by means of a laser triangulation sensor that performs a relative movement between the tool and the component. This point cloud then allows precise positioning of the additive structure. Such an active, direction-independent triangulation sensor was developed at Fraunhofer IAPT [Buh22].

In combination with the higher material offset found in near-net-shape DED parts (which allows further more tolerance in measuring), positioning the additive DED structure on the part surface is usually easier than with PBF processes.

With powder-bed processes, the respective clamping for the build platform must be considered. The build platforms are not originally designed for hybrid components, but for printing the entire component on the base plate and subsequent removal from it. In addition to clamping, the ensuing levelling of the parting plane is also very time-consuming owing to the tilt angle or unevenness of the semi-finished product. This therefore leads to a considerable setup time for a hybrid manufacturing process.

Here, too, the calibration of the semi-finished part is very crucial, as an incorrect value will result in the PBF structure not being printed at the target position (particularly critical with rotational parts). To avoid the clamping problem, zero-point clamping systems are predominantly used. For example, the companies AMF [And20] or MostTech [Mos18] have developed their own systems for this purpose. In addition, a zero-point clamp for process temperatures up to 800°C is currently being developed for the PBF process in an ongoing research project between Fraunhofer IPK and AMF. However, the zero-point clamping system has the disadvantage that it entails a reduced maximum possible component height. It also requires machined surfaces in the semi-finished product to ensure a proper fit in the clamping tool. Therefore, the current alternative is only manual, using mechanical fasteners to attach the parts to the building platform.

There are currently two methods available for measuring the base part/geometry in the hybrid PBF process. One is to use a structured light projector to generate a point cloud, the other is to use a moving triangulation sensor. However, both variants must be located within the process chamber, which is a limitation.

A new approach provides a three-dimensional videometric calibration based on the triangulation principle of a stereo vision camera system [Fra21]. Here, the corresponding points of captured images in different cameras are calculated [Dal14]. Thereby the three-dimensional position is determined in the form of a point cloud [Kle 08]. Currently, the method is used in an LPBF process for monitoring weld spatter [Bar18; Bar19; Esc19] or for monitoring the printed component [Li18]. The key advantage of stereo vision for hybrid manufacturing over other solutions is the positioning of the cameras outside the process chamber of a LAM system. This means that the machine integrity is not tampered [Esc19] and can be retrofitted manually.

In both cases, positioning accuracy is a decisive factor and should never be neglected when designing the parting plane or the overall design of the hybrid component. If a material overbuild can be allowed and calculated, i.e. printing more material than ultimately necessary and subsequent machining, the complexity of the correct positioning is simplified. However, if specific features on the base must be met precisely, the positioning effort increases enormously. Especially with freeform deposition over up to eight axes (DED), the smallest positioning inaccuracies lead to a cumulative error.

»

Hybrid additive manufacturing has the potential to significantly change the value chain in 3D printing.«

Figure 16: A critical analysis of the research results is always part of Fraunhofer IAPT's business

8. Hybrid additive manufacturing guide

This chapter is meant to help identify potential use cases for hybrid additive manufacturing in companies. For this purpose, the economic aspects of the design are considered first, followed by the identification of a suitable hybrid approach based on the technical criteria. Depending on the hybrid approach, checklists are helpful in answering the relevant questions during the design process. The chapter concludes with an overview of different hybrid components and explains the rationale behind each component.

8.1 Identification of cost-saving potentials

Since the economic aspect is usually the most important factor in industrial component design, the printing costs of different suppliers are initially compiled in a standardised form for a demonstrator component. The component can be manufactured using both the PBF and DED processes and therefore does not represent the entire spectrum of AM component possibilities. Rather, the aim is to obtain an average value for the costs of the example component from different suppliers. Adjusted to €/cm³, this provides an indication of how much printing cost per saved volume of the component is potentially possible. Even though this is a highly simplified approach, it can still be used to quickly evaluate the hybrid capability of the component.
It is well known that standard semi-finished products and conventional manufacturing processes have a cost advantage over printed components in most cases. A hybrid approach is only cost-effective if the saved printing volume and thus the printing costs justify an additional process step (e.g. joining). However, the assessment of the extra costs associated with an additional joining process are not easy to standardize and greatly depend on the application.

Figure 18 shows the standardised manufacturing costs for a component using the LPBF process, used to determine the average costs. The printing costs, in some cases, vary greatly due to different terms and conditions of the offers, among others.

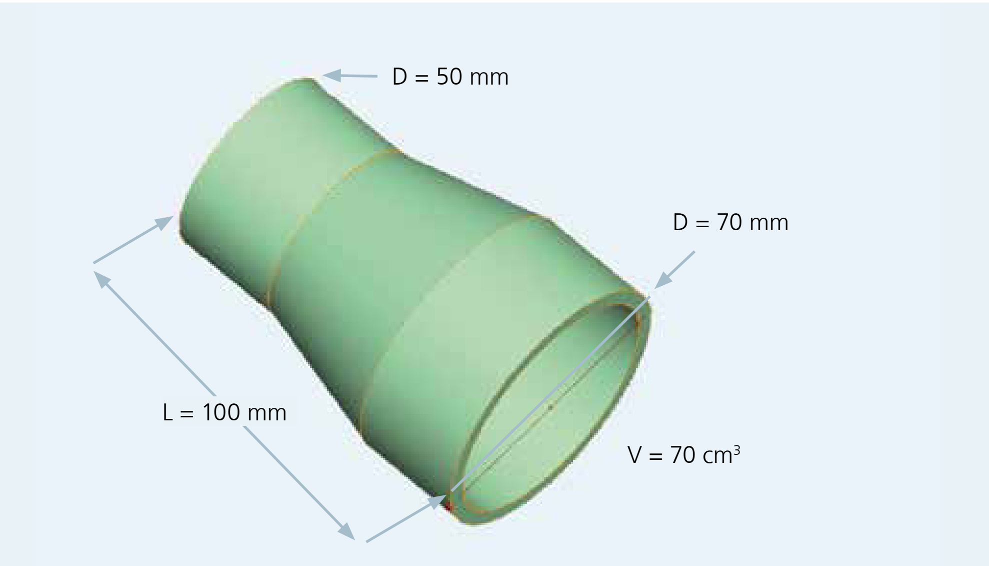


Figure 17: Requested reference component for a cost determination in the LPBF and DED processes

Highly variable printing costs complicate the profitability analysis

As predicted, printing costs decrease with higher volumes, which at first glance reduces the savings potential of the hybrid design. Nevertheless, this savings potential must also be considered for any other manufacturing process. Joining a single component results in high one-time costs for setup, programming, etc. However, these are no longer a factor for larger quantities.

Looking beyhond material costs

Besides the results for aluminum, a very similar range of figures was established for the adjusted/standardized printing costs for stainless steel 1.4404, titanium Ti-6Al-4V and the nickel-based alloy In625. However, as a conventional raw material, stainless steel is significantly cheaper compared to the other two materials. A hybrid design is therefore particularly advantageous for this material, since relatively high printing costs can be saved by using inexpensive semi-finished products. The similar printing costs, despite the lower powder price for stainless steel compared to titanium or nickel (about a factor of three), result from the feasibility constraints of steel materials in the LPBF process. Even with optimised process parameters, printing can only be carried out at a comparatively low scanning speed, which leads to higher machine usage times and therefore higher costs.

Overview of LPBF Costs adjusted to €/cm³ for the example part »tube connector«

Figure 18: Overview of LPBF costs

DED offers high savings potential with increasing unit numbers

Due to the limited data available, only the values for the material 1.4404 are shown in the following overview of the DED process costs (Figure 19). Laser powder, laser wire and WAAM processes (Wire Arc Additive Manufacturing) have been considered and are included in the graph. Since not enough data is available for each process, no individual average value can be calculated. The average value for the »DED process« must therefore be viewed as highly simplified, as the processes with their individual advantages and disadvantages also result in very different cost structures.

However, it is apparent that in series production (based on this component) the costs are greatly reduced, and that the normalised costs between the processes are also very similar. This is due to the high one-time cost for the toolpath planning and programming of the machine, which is a major disadvantage for a lot size of one of DED processes.

With increasing production lot sizes, the one-time programming costs no longer have such a strong impact on the unit costs. The process can then »score« in terms of costs thanks to their comparatively high deposition rates and thus low machine occupation times.

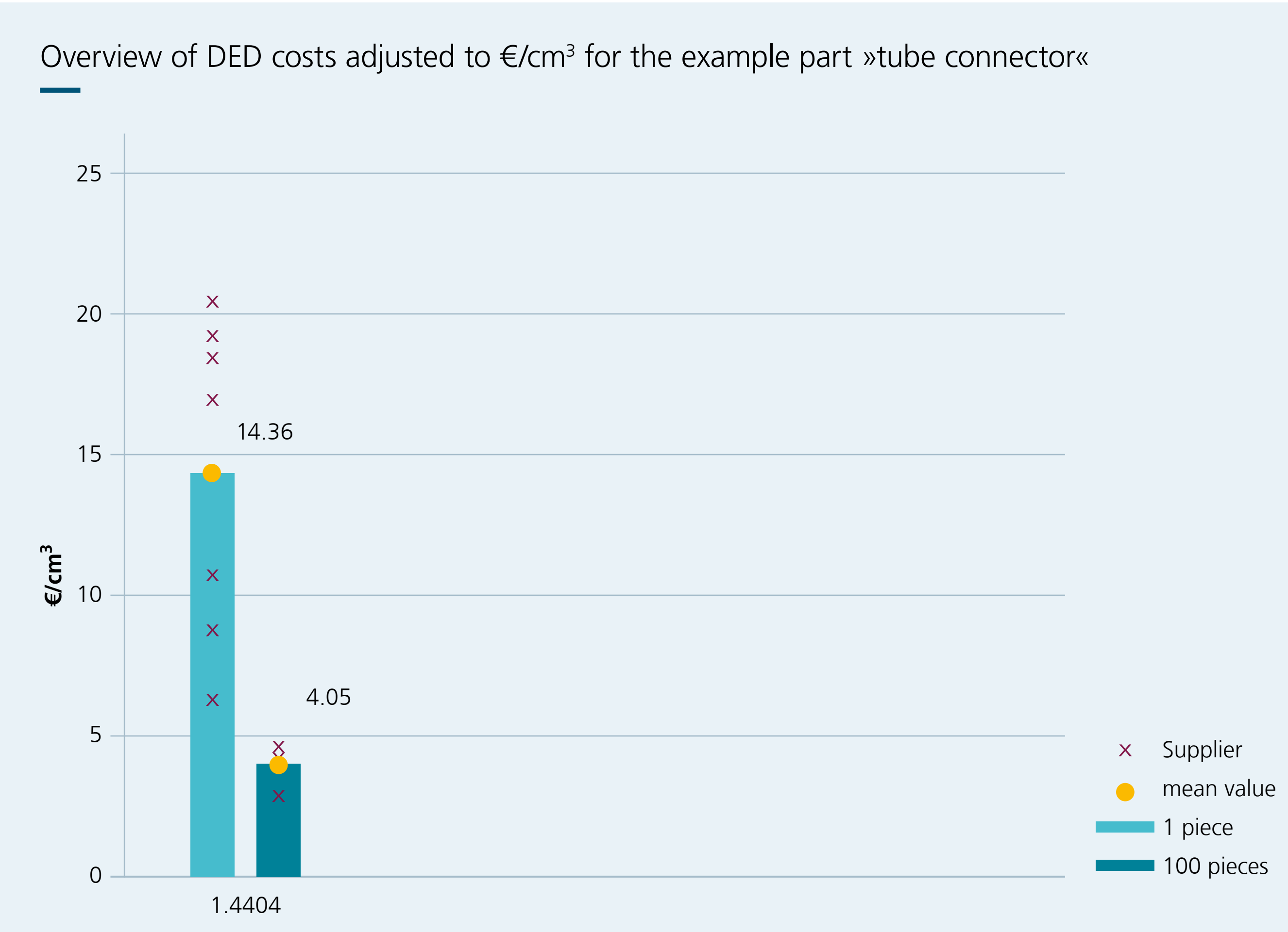


Figure 19: Overview of DED costs

8.2 Identification of a suitable hybrid AM approach

For further technical consideration, an evaluation matrix is presented in Table 4, comparing different input variables from the application scenario with specific hybrid AM approaches. The matrix allows an approximate assessment of the most suitable approach depending on the respective input variables. In addition to the three hybrid approaches, a comparison is also made with the AM-only process (subdivided into powder bed and DED processes) and the pure conventional approach. Once a suitable hybrid AM approach is selected, the characteristics outlined in chapter 7 must be considered. For a quick overview, relevant questions are summarized in the checklist included below for each approach. These are intended to support the component design and the development of a hybrid manufacturing process chain. In addition to the questions on the design and structure of the process chain, other topics are also listed here.

Some of them are highly individually and depend on the selected process chain. They usually cannot be simply answered with a »yes« or »no«. These topics are included in the checklist to ensure that process-specific features are not forgotten in the overall design of the process.

Component parameters and (hybrid) manufacturing approaches

Suitable for	Joining of AM and conventional parts	Printing on conventional part (LPBF)	Printing on conventional part (DED)	LPBF only	DED only	Conventional
Large dimensions	●	●	●	○	●	●
Bulky volume	◐	○	●	○	◐	●
High part complexity	●	◐	◐	●	○	○
High surface quality of the printed surface	◐	◐	○	◐	○	●
Light-weight design	●	●	◐	●	○	◐
High number of part variants or customisable features	●	●	◐	●	◐	○

● good ◐ neutral ○ poor

Table 4: An evaluation matrix for assessing part suitability and several (hybrid) manufacturing approaches

1. Checklist: Joining individual components

Considerations		
Which welding process should be used? Is it suitable for the application?	*	
Is the material pairing weldable with the selected process?	◯ Yes	◯ No
Is it possible to weld the materials at room temperature? If not, consider pre-heating.	◯ Yes	◯ No
Accessibility for the welding head ensured in the part design?	◯ Yes	◯ No
Can the components be easily positioned/clamped for welding?	◯ Yes	◯ No
Is the joining zone design (position, geometry) considered?	◯ Yes	◯ No
Preparation of the pre-weld surface : - »As built« surface weldable? Machining necessary? - Cleaning necessary to avoid instabilities during welding?	*	
Preparation of the post-weld surface: - Machining of the weld seam necessary? - Sand blasting, polishing etc. necessary?	*	
Reworking of the hybrid component as a whole necessary? - Balancing of rotating components - Production of dimensionally assigned functional surfaces	*	
Microstructure and properties of the weld considered? (hardness, microstructure formation, heat-affected zone)	◯ Yes	◯ No
Heat treatment necessary before and/or after welding?	◯ Yes	◯ No
Are tack welds necessary to avoid welding distortion?	◯ Yes	◯ No
Can the structurally necessary weld seam cross-sections be realised?	◯ Yes	◯ No
Does the welding process need a specific shielding gas?	◯ Yes	◯ No
Which handling system for the welding head fulfils the requirements defined by the part? How many degrees of freedom are necessary?	*	
Is it necessary to remove weld spatter? How to avoid weld spatter?	*	

* Please describe

2. Checklist: Printing on a base plate or part using LPBF

Considerations		
Is the material to be printed available as powder and qualified for the LPBF process?	◯ Yes	◯ No
Is the base material laser weldable? (carbon equivalent, gas pores, crack formation)	◯ Yes	◯ No
Realisation of a flat, horizontal parting plane parallel to the exposure plane is technically possible and easy to define?	◯ Yes	◯ No
Is it easily possible to integrate the base plate into the build platform?	◯ Yes	◯ No
Is it possible to integrate the base into the building platform of a standard machine? Are there any cavities that need to be filled with powder before the first layer is printed?	◯ Yes	◯ No
Do the tolerances of the base plate allow an accurate integration into the building platform with the required accuracy?	◯ Yes	◯ No
What is the concept to connect the base plate to the building platform?	*	
Is this connection still accessible for loosening after printing?	◯ Yes	◯ No
Is it possible to ensure a sufficiently accurate absolute positioning and orientation of the base plate in the working space of the machine?	◯ Yes	◯ No
Does the part to be printed require support structures? If yes, these must be placeable on the base plate or already printed part	◯ Yes	◯ No
Is it possible to place more than one base plate into the building platform to increase the efficiency of the process?	◯ Yes	◯ No
Is the surface of the part to be printed suitable for an LPBF process in terms of roughness? (e.g. printing on a cast or forged part).	◯ Yes	◯ No
Are there internal channels through the parting plane? Can the powder remaining there be removed later?	◯ Yes	◯ No
Does the base plate withstand a heat treatment necessary for the printed segment afterwards?	◯ Yes	◯ No

* Please describe

3. Checklist: Printing on a base plate or part using DED

Considerations		
Which material has to be deposited? Is it available in wire and or powder form?	*	
Which DED technology suits your application? (accuracy, availability, material form, …)	*	
Is the base plate material suitable for deposition welding?	◯ Yes	◯ No
Does the base plate need a preheating before welding?	◯ Yes	◯ No
Which areas of the printed part need additional machining? Are they accessible after printing?	◯ Yes	◯ No
Is a 5-axis movement system needed? Are 3 axes (X, Y and Z) sufficient?	◯ Yes	◯ No
How to clamp the base plate to prevent distortion during deposition welding?	*	
Can/must the base plate be protected against weld spatter? How can weld spatter be prevented or removed afterwards?	*	
Can/must the thermal deformations of the base body caused by welding be compensated?	◯ Yes	◯ No
Can the entire component be heat treated after the additive process to reduce residual stresses? If necessary, together with the clamping device?	◯ Yes	◯ No
Should the base plate already have its final shape before deposition welding or should/can it be machined afterwards together with the printed section to the final dimension?	◯ Yes	◯ No

* Please describe

»WAAM-printed components can be further refined with hybrid manufacturing.«

Figure 20: This part of an aircraft door is a use case for manufacturing a hybrid component with welded-in reinforcing plates

9. Use case demonstration

9.1 Joining of additively manufactured and conventional parts

This chapter describes examples of hybrid AM parts using the approaches outlined in chapter 6.1.3

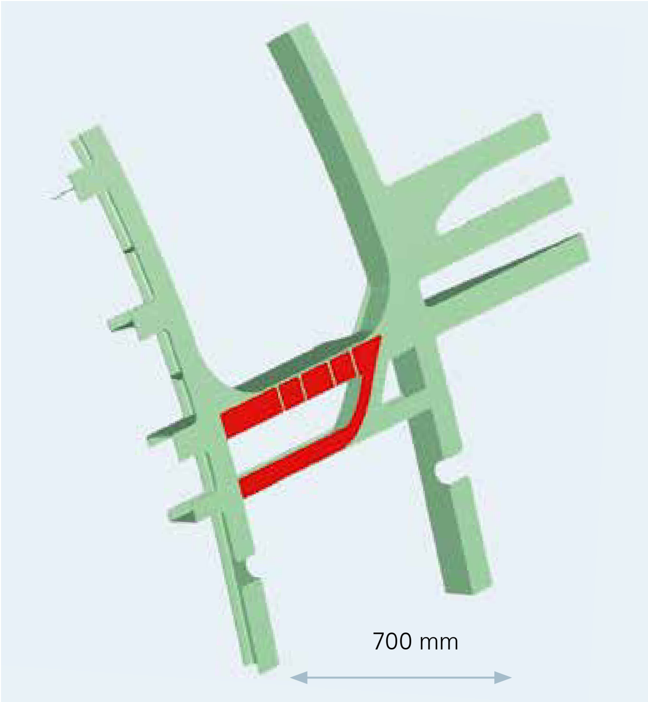


Figure 21: W-DED-printed aircraft door surround with integrated reinforcement plates, welded into the printed base structure

9.1.1 Reinforcement structure for aircraft door surrounding

As part of the publicly funded research project »REGIS« (FKZ 20W1708E) for the realisation of additively manufactured integral structures, hybrid design methods for large components in Ti-6Al-4V were investigated at Fraunhofer IAPT. The component manufactured as a demonstrator for this technology is a section of an internal reinforcement structure of an aircraft outer skin surrounding the emergency exits above the wings. The demonstrator was printed in Ti-6Al-4V using WAAM (Wire Arc Additive Manufacturing). The component is printed near-net-shape on a pre-bent substrate using WAAM in order to reduce the amount of machining required for the final geometry (Figure 21). The entire DED surface must be machined after the printing process. Once this subtractive process step has been completed, conventional reinforcement plates are welded into the areas that will later be subject to high mechanical loads by means of a laser welding process.

Motivation for a hybrid approach:
The main driver for this hybrid approach is not only the size of the final component to be produced, but also requirements resulting from the component geometry that do not allow complete printing. If the geometry of the subsequently welded-in sheet metal were to be printed using the WAAM process, a circumferential mechanical milling of the component would not be possible or would only be possible to a limited extent using special milling cutters. This is because undercuts on the component would mean that not all areas would be accessible with standard milling equipment.

Hybrid approach:
During this anyway necessary milling process, the joining zones on the printed part (shown in green in the illustration) are prepared in such a way that the reinforcing sheets (shown in red) can later be welded in reliably using laser welding technology. For this purpose, a small material deposit is created along the welding line in the printed component at the edge of the component. It flows into the fusion zone during welding as »additional material« and effectively prevents a possible seam undercut. Preliminary assessment in the project demonstrated that the laser welded joint of Ti64 printed in WAAM with conventional titanium sheet meets the strength requirements according to AIMS03-29-001 [AIR18] for Metallic Wire Direct Energy Deposition of Ti-6Al-4V.

Conventional part:
In this application, the conventional parts (titanium sheets) are cut out of a prebent titanium sheet according to the required geometry by means of wire erosion.

AM process:
Directed Energy Deposition using arc and wire.

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

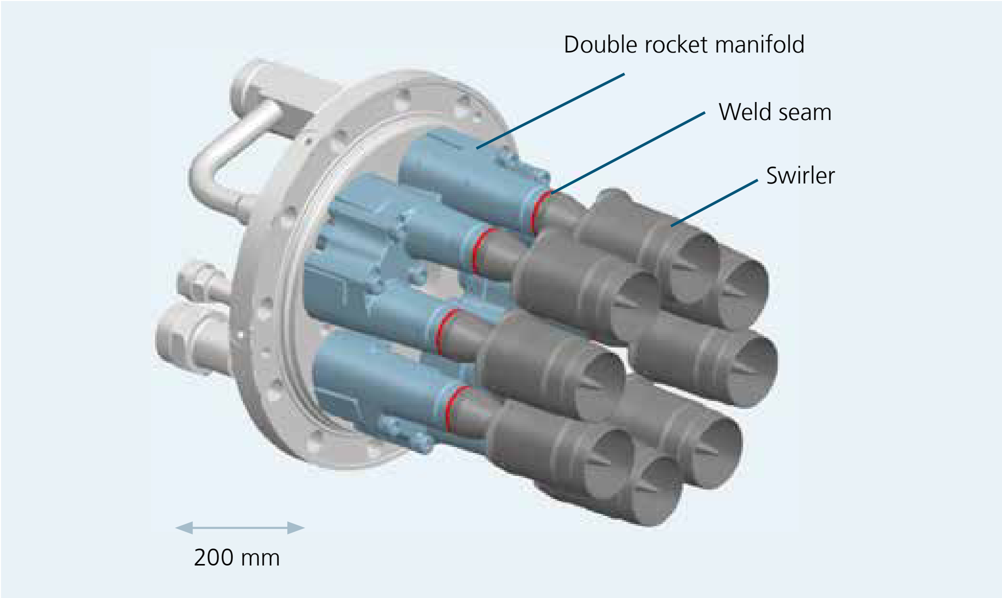


Figure 22: SGT-8000(H) combustion system with weld seams between swirlers and manifolds [Gei22]

9.1.2 Combustion system for gas turbines

Geisen et.al. [Gei22] describe a study for integrated weld preparation designs for the joining of LPBF printed and conventional components, manufactured in In625 via TIG welding to produce the combustion system for stationary gas turbines (Figure 22).

Motivation for a hybrid approach:

The main issues for this hybrid approach are the build size limitation and the high production costs for LPBF parts. The expensive and usually complex components, printed in LPBF are to be reduced in their size and joined to conventionally manufactured and less complex elements. Without a special preparation of the joining area, this process currently requires highly complex fixtures to ensure correct alignment and fixation for the joining process.

Due to the size of the components and the mechanical processing required on the parts shown in light blue (Figure 19), it is not possible to print these and the grey parts together in one piece.

Hybrid approach:

The parts to be joined require extremely precise positioning of the swirler relative to the manifold in terms of centring (0.5 mm), rotational orientation (< ±1°) and axial length (± 0.6 mm).

By integrating snap-fit or, alternatively, bayonet elements into the joining area, a tack welding process cycle is now no longer required. In addition to eliminating the previously used external clamping, the snap-fit or bayonet design also enable the desired positioning in the required accuracy.

Conventional part:

The cast manifold needs some mechanical preparation in the welding area. The overall concept for the joining area requires simple mechanical geometry on the manifold side and more complex (and difficult to manufacture) geometries on the printed side at the swirler.

AM process:

Laser Powder Bed Fusion

9.2 Printing on conventional parts with Powder Bed Fusion

9.2.1 Expansion mandrel
Many production processes require mandrels to fix tools or workpieces during production or assembly. Most of these mandrels are specially designed for the geometry requirements of the individual application. By using 3D printing technology, it is now easy to create individual expansion mandrels for several applications.

Motivation for a hybrid approach:
In addition to the functional area of an expansion mandrel, a standard »handling adapter unit« is always required to affix it on a standard machine. This adapter is a »high-volume« part that usually does not have highly complex geometrical features, but sometimes has high demands on geometrical accuracy. Therefore, it is both easy and recommended to manufacture this part using conventional milling or turning technology and combine it with the individually printed component.

Hybrid approach:
If an expansion mandrel is made using two subcomponents manufactured with different technologies, it is necessary to guide hydraulic fluid under pressure through the joining plane. For this application it is logical to print the 3D-generated part directly onto the joining surface in order to continue the bore-holes for the hydraulic fluid inside the mandrel. This offers a high safety level for a leak-free joining, compared to conventional joining with a flat seal between the two components. Figure 23 depicts such a component, consisting of a standard base unit (left side) and an application specific part printed directly on the base.

Conventional part:
Although the conventional component requires a sophisticated joining surface, the mechanical design is very simple and reduced to a plane which includes one (or more) bores for hydraulic fluid.

AM process:
Laser Powder Bed Fusion

Figure 23: Expansion mandrel, directly printed to a standard base unit, using LPBF technology

9.2.2 Bell-shaped tool for machining outside diameter

Today, application-specific PCD tools are increasingly used in mass production. In addition to a customised geometry, the weight plays an important role in assessing the economic efficiency. The technical properties of this hybrid aproach are explained using the example of the bell-shaped tool from Mapal [Map20] shown in Figure 24. This tool is used, for example, for external machining of hose connections.

Motivation for a hybrid approach:
As described above for the expansion mandrel, the main driver for this approach is the use of a conventionally manufactured standard base body as a clamping fixture. In this application, the weight of the tool was reduced by approximately 30% thanks to the integration of honeycomb structures in the additively manufactured part. According to the manufacturer, the damping properties of the honeycomb structure increased the tool life by about 40%.

In addition, the cooling channel guidance in the printed part was optimised so that the machining time of the hybrid version is reduced by 50% compared to a conventionally manufactured version of this tool.

Hybrid approach:
The application-specific geometry of the tool is printed on the standardised basic clamping body, using the LPBF process. After printing, slight mechanical finishing is carried out (balancing and milling of the receptacles for the PCD cutting edges). The PCD cutting edges are then finally soldered into the tool and shaped by laser.

Conventional part:
A conventional base with HSK-63 interface is used as the clamping body, which is conventionally manufactured in large quantities.

AM process:
Laser Powder Bed Fusion

Figure 24: Bell-shaped tool for outside diameter processing, printed on a standard basic clamping body using LPBF [Map20]

9.3 Printing on conventional parts with Directed Energy Deposition

9.3.1 First FAA-approved structural titanium component

The component shown in Figure 25 is the first OEM-qualified, FAA-approved, additively manufactured structural titanium component. It is made by Norsk Titanium [Nor22] using their Rapid Plasma Deposition® (RPD®) process. Thousands of tests on fatigue, fracture strength, damage tolerance, elevated temperature, etc. were successfully mastered. The component is now installed in the tail of the Boeing 787 Dreamliner. From a manufacturing point of view, it is simple in design and consists mainly of flat surfaces arranged as ribs, cross braces and angled flange surfaces with good accessibility for milling tools.

Motivation for a hybrid approach:
The price of an aircraft part depends less on the price of the material, but rather on the many hours of machining required to produce it from a block or a forging blank. In order to shorten or reduce the necessary machining steps, a near-net-shape contour is required as the input geometry for final machining. The motivation for a hybrid approach is thus based on both cost and resource savings.

Hybrid approach:
The RPD® process causes increasing costs depending on the volume to be built up. For technological reasons, RPD® processes require a base plate, which is a cheap semi-finished product. Therefore, by intelligently placing the base plate in the part design, two challenges are met: substituting the volume to be built up with a low-cost semi-finished product and, at the same time, providing a base plate for the RPD® process.

Conventional part:
A titanium ingot is machined into 90% chips and 10% final components.

AM process:
Directed Energy Deposition using plasma arc and wire, Rapid Plasma Deposition®

Figure 25: FAA-qualified aircraft structural component from Norsk Titanium, manufactured with Rapid Plasma Deposition® [Nor22]

9.3.2 Metal leading edge

Metal leading edges are used in the first stage blades of aircraft engines to protect them against bird and stone impact. For weight reasons, these fan blades, which generate the main thrust in turbofan engines, are made of composite material and not entirely of metal.
The metal leading edge is made of titanium and has a complex shape that is twisted three-dimensionally. In addition to impact protection, it must have a minimum weight as a second criteria. Figure 26 shows the entire process chain needed to manufacture this highly complex part.

Motivation for a hybrid approach:
With a length of over one meter and titanium as the material, this part is very cost intensive, it requires a lot of machining and generates a lot of material waste. The motivation for a hybrid approach is therefore savings of both costs and resources.

Hybrid approach:
Since additive manufacturing is still very costly, the approach is to have as much material of the final part made from a conventional semi-finished product. For this, a 3 mm thin tube is forged in two stages into the complex three-dimensional basic shape of the turbine blade. To account for the different wall thicknesses along the edge, additional material is deposited in a next step using the DED process. In addition to heat treatment, the final product requires machining and cutting the part out of the tube with a minimum of material waste.

Conventional part:
Titanium tube as the semi-finished product with a two-stage forging process.

AM process:
Directed Energy Deposition using laser and powder

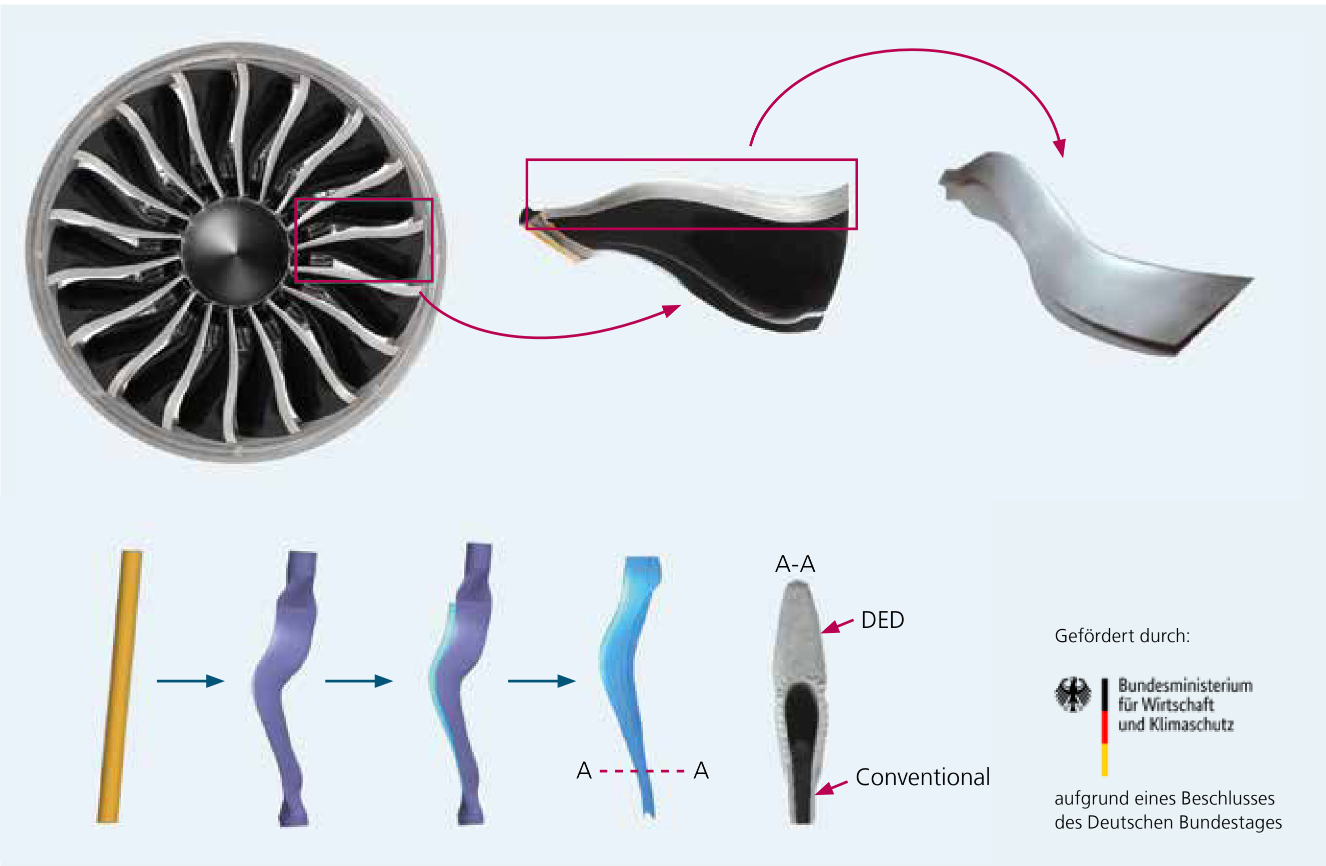


Figure 26: Hybrid approach to produce the metal leading edge of an aircraft engine fan blade

Figure 27: A use case for joining additively manufactured and conventional parts: a section of an internal reinforcement structure of an aircraft outer skin surrounding the emergency exits above the wings

10. Summary & Conclusion

In this Deep Dive, the opportunities of manufacturing components with a hybrid design concept, combining conventionally manufactured and 3D printed segments, are analysed. The term »hybrid« is introduced in a discriminating way and examples are used to explain in more detail how the concept of hybrid design can be understood. The key motivation factors for hybrid additive manufacturing are the reduction of costs, an increase in component size, the accessibility during printing as well as a reduction of the complexity of individual parts.

The focus of this report is on the combination of conventionally manufactured semi-finished products with a 3D-printed segment. This combination can be realized either by directly printing on the part or by subsequently joining the different segments. With regard to additive manufacturing technologies, the assessment is limited to Laser Powder Bed Fusion (LPBF) and Directed Energy Deposition (DED) technologies. A high potential of hybrid design applications is already known for these technologies.

As far as joining of component segments is concerned, additive manufacturing provides completely new possibilities for joining zone preparation. The Deep Dive presents different joining zone designs that go beyond today's conventional processes. Initial evaluations confirm that a significant value can be added by directly integrating aids for joining in the 3D-printed component. With this approach, the effort – and thus costs – for clamping and positioning can be reduced.

Depending on the AM process, the challenges in applying the additive segment directly onto a semi-finished product arise from clamping and positioning. Particularly in the case of filigree structures in the LPBF process, high tolerance requirements must be met. It should be noted that in this approach, the parting plane between two segments can only be a single plane. In DED technologies, the tolerance requirements are less rigorous, as these processes contain a lower resolution.

Nevertheless, thanks to the high flexibility (build-up direction not only in z direction), several parting planes are possible with deposition technologies. This advantage is in turn associated with very tight tolerance requirements of the component, which result from the correlation of inaccuracies between the different build directions.

In order to assess whether a component is suitable not only for 3D printing but also for hybrid 3D print design, the costs incurred can be considered first and foremost. Therefore, this Deep Dive features a simplified assessment of the printing costs of a reference component. The calculation approach was standardized for different materials in relation to a volume size. This tool facilitates the identification of potential cost savings in the printing process resulting from a reduction in print volume due to the hybrid design. A hybrid design concept should only be considered if a high cost-saving potential is identified.

In the LPBF process, the highest savings potential is achieved when processing the stainless-steel material 1.4404 considered here. Owing to the technical limitation of the printing speed, similar standardized printing costs are determined as for titanium or nickel materials, despite the less expensive powder material. Thus, in the production of hybrid components, the highest cost savings can be achieved by taking advantage of the comparatively low-cost stainless steel semi-finished material.

Figure 28: The Deep Dive presents several success stories in additive manufacturing

Furthermore, the differentiated analysis of batch sizes 1 to 100 indicates a significant difference between the DED processes. For the cost analysis, laser powder, laser wire and arc wire deposition technologies are aggregated.

Despite the partially distinct differences in the cost incurrence, it is evident for all processes that the high one-off expense in programming can be reduced to only 30% of the costs for batch size 1 by increasing the number of pieces.

Moreover, in order to be able to better assess whether a hybrid design concept for a component has merit from a technical point of view, checklists were devised to support the consideration of the most important design criteria. Three application scenarios are examined in more detail: Joining of individual components, printing on a base plate or a part using LPBF, and printing on a base plate or a part using DED.

Finally, the Deep Dive presents several success stories featuring hybrid additive manufacturing. As part of this, the rationale and technical solutions for hybrid manufacturing are outlined.

To conclude, the hybrid additive manufacturing approach expands the opportunities for economic and technical business cases in 3D printing. That said, each individual case requires specific considerations for an appropriate process strategy.

11. References

[Aer22] Aerosint SA, "Multi-Material 3D Printing Bundle for Laser Powder Bed Fusion system", https://aerosint.com/multi-material-3d-printing-bundle/, 2022.

[Air18] Airbus Material Specification, "AIMS03-29-001 Additive Manufacturing Metallic Wire Direct Energy Deposition Titanium Alloys Ti-6Al-4V. 06/2018", 2018.

[Air22] Airbus Operations GmbH, Premium AEROTEC GmbH, Stiftung Institut für Werkstofftechnik, GEFERTEC GmbH, Technische Universität Hamburg, BIAS – Bremer Institut für angewandte Strahltechnik GmbH, Forschungsprojekt REGIS – Realisation of additively manufactured integral structures, hybrid design methods for large components in Ti-6Al-4V. FKZ 20W1708E, 2022.

[Akb19] AKBARI M., KOVACEVIC R., "Joining of elements fabricated by a robotized laser/wire directed energy deposition process by using an autogenous laser welding", *The International Journal of Advanced Manufacturing Technology*, vol. 1009-12, 2019, p. 2971-2980.

[And20] Andreas Maier GmbH & Co. KG, www.amf.de/de/aktuelles/news-und-produktneuheiten/nullpunktspanntechnik-ist-in-der-additiven-fertigung-unumgaenglich-277, 2020.

[Bar18] BARRETT C., CARRADERO C., HARRIS E., WALKER J., MCKNIGHT J., MACDONALD E., CONNER B., Low Cost, "High Speed Stereovision for Spatter Tracking in Laser Powder Bed Fusion". University of Texas at Austin, 2018.

[Bar19] BARRETT C., CARRADERO C., HARRIS E., ROGERS K., MACDONALD E., CONNER B., "Statistical analysis of spatter velocity with high-speed stereovision in laser powder bed fusion", Progress in Additive Manufacturing, vol. 4 no. 4, 2019, p. 423-430.

[Bec15] BECKMANN F., EMMELMANN C., "Hybrid lightweight design by laser additive manufacturing and laser welding processes", Lasers in Manufacturing Conference 2015, 2015.

[Bec17] BECKMANN F., EMMELMANN C., "Optimization of laser welding process for laser additive manufactured aluminum parts by means of beam oscillation and process-oriented component design", Lasers in Manufacturing Conference 2017, 2017.

[Bif19] BIFFI C. A., FIOCCHI J., TUISSI A., "Laser Weldability of AlSi10Mg Alloy Produced by Selective Laser Melting: Microstructure and Mechanical Behavior", *Journal of Materials Engineering and Performance*, vol. 28 no.11, 2019, p. 6714-6719.

[Buh22] BUHR M., VYKTHAR B., EMMELMANN C., "Multidirectional Sensing for Digitalization", Additive Manufacturing Applications, 2022.

[Cai21] CAIAZZO F., ALFIERI V., "Optimization of laser beam welding of steel parts made by additive manufacturing", *The International Journal of Advanced Manufacturing Technology,* vol. 1149-10, 2021, p. 3123-3136.

[Dal14] DALL'ASTA E., RONCELLA R., "A comparison of semi-global and local dense matching algorithms for surface reconstruction", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5, 2014, p. 187-194.

[Dmg22] DMG MORI, "LASERTEC 125 DED hybrid", https://de.dmgmori.com/produkte/maschinen/additive-manufacturing/pulverdueseverfahren/lasertec-125-ded-hybrid, 14.09.2022

[Dim22] DIMATTEO V., LIVERANI E., ASCARI A., FORTUNATO A., "Weldability and mechanical properties of dissimilar laser welded aluminum alloys thin sheets produced by conventional rolling and Additive Manufacturing", *Journal of Materials Processing Technology*, vol. 302, 2022, p. 117512.

[Esc19] ESCHNER E., STAUDT T., SCHMIDT M., "3D particle tracking velocimetry for the determination of temporally resolved particle trajectories within laser powder bed fusion of metals", *International Journal of Extreme Manufacturing*, vol. 1 no. 3, 2019, p. 35002.

[Fra20a] Fraunhofer-Einrichtung für Additive Produktionstechnologien IAPT, Forschungsprojekt HydroAdd – Entwicklung eines additiv gefertigten Hydrodehnspannfutters mit integrierter Sensorik für Industrie 4.0-Anwendungen – FKZ ZF4547815RP8, 2020.

[Fra20b] Fraunhofer-Institut für Gießerei-, Composite- und Verarbeitungstechnik IGCV, "Jahresbericht 2019/2020", 2020.

[Fra21] Fraunhofer-Einrichtung für Additive Produktionstechnologien IAPT, Entwicklung der Systemtechnik zur Fertigung hybrider LBM-Bauteile. AiF-Projekt 22075 N. 2021, 2021.

[Gei22] GEISEN O., MÜLLER V., GRAF B., RETHMEIER M., "Integrated weld preparation designs for the joining of L-PBF and conventional components via TIG welding", Progress in Additive Manufacturing, 2022.

[Hau21] HAUSER T., REISCH R. T., SEEBAUER S., PARASAR A., KAMPS T., CASATI R., VOLPP J., KAPLAN A. F., "Multi-Material Wire Arc Additive Manufacturing of low and high alloyed aluminium alloys with in-situ material analysis", *Journal of Manufacturing Processes,* vol. 69, 2021, p. 378-390.

[Haw22] HAWK C., SIMONDS B., TANNER J., PACHECO R., BRAND M., VIGIL G., JAVERNICK D., LIU S., "Laser spot welding of additive manufactured 304L stainless steel", *Welding in the World*, vol. 66 no. 5, 2022, p. 895-906.

[Hen19] HENCKELL P., ALI Y., METZ A., BERGMANN J. P., REIMANN J., "In Situ Production of Titanium Aluminides during Wire Arc Additive Manufacturing with Hot-Wire Assisted GMAW Process", *Metals*, vol. 9 no. 5, 2019, p. 578.

[Hyb22] Hybrid Manufacturing Technologies, hybridmanutech.com/portfolio/swedish-mega-project/, 2022.

[Jae19] JAESCHKE N., LINGNER M., GOUSHEGIR S. M., SENKEL Y., BECKMANN F., "Bionischer LAM-Stahlleichtbau für den Automobilbau – BioLAS", edocs.tib.eu/files/e01fn20/1689622865.pdf, 2019.

[Jok19] JOKISCH T., MARKO A., GOOK S., ÜSTÜNDAG Ö., GUMENYUK A., RETHMEIER M., "Laser Welding of SLM-Manufactured Tubes Made of IN625 and IN718", Materials, vol. 12 no. 18, 2019.

[Kle08] KLEIN K., Automatisierung der 3D-Rekonstruktion aus mehreren Tiefenbildern durch Optimierung prädizierter Qualitätsgewinne. TU Darmstadt, 2008.

[Kum21] KUMAR M. S., RAJESH KANNAN A., PRAVIN KUMAR N., PRAMOD R., SIVA SHANMUGAM N., VISHNU A. S., CHANNABASAVANNA S. G., "Microstructural Features and Mechanical Integrity of Wire Arc Additive Manufactured SS321/Inconel 625 Functionally Gradient Material", *Journal of Materials Engineering and Performance*, vol. 30 no. 8, 2021, p. 5692-5703.

[Lei20] LEICHER M., KAMPER S., TREUTLER K., WESLING V., "Multi-material design in additive manufacturing – feasibility validation", *Welding in the World*, vol. 64 no. 8, 2020, p. 1341-1347.

[Lei22] Leistritz Turbinentechnik GmbH, Access E.V., Fraunhofer-Einrichtung für Additive Produktionstechnologien IAPT, Forschungsprojekt IKARUS – Innovative Herstellung von Eintrittskanten-Abdeckungen – Ein Beitrag zur Ressourcen- und Umweltschonung. FKZ 20T1908C, 2022.

[Li18] LI Z., LIU X., WEN S., HE P., ZHONG K., WEI Q., SHI Y., LIU S., "In Situ 3D Monitoring of Geometric Signatures in the Powder-Bed-Fusion Additive Manufacturing Process via Vision Sensing Methods", Sensors, vol. 18 no. 4, 2018.

[Map20] MAPAL Fabrik für Präzisionswerkzeuge Dr. Kress KG, "Mit additiver Fertigung zu mehr Produktivität – Glockenwerkzeug zur Außenbearbeitung von MAPAL", news.mapal.com/de-de/a/glockenwerkzeug, 2020.

[Mat16] MATILAINEN V.-P., PEKKARINEN J., SALMINEN A., "Weldability of Additive Manufactured Stainless Steel", *Physics Procedia*, vol. 83, 2016, p. 808-817.

[Mat22] MATSUURA Europe GmbH, https://www.matsuura.de/produkte/additive-manufacturing, 13.10.2022.

[Mic21] MICHLER M., HOLLMANN P., ZENKER R., BUCHWALDER A., "Investigation of Pore Reduction in Hybrid Joints of Conventionally and Additively Manufactured AlSi10Mg Using Electron Beam Welding", *Advanced Engineering Materials*, vol. 23 no. 6, 2021, p. 2001325.

[Mok21] MOKHTARI M., POMMIER P., BALCAEN Y., ALEXIS J., "Laser Welding of AISI 316L Stainless Steel Produced by Additive Manufacturing or by Conventional Processes", *Journal of Manufacturing and Materials Processing,* vol. 5 no. 4, 2021, p. 136.

[Möl20] MÖLLER B., SCHNABEL K., WAGENER R., KAUFMANN H., MELZ T., "Fatigue assessment of additively manufactured AlSi10Mg laser beam welded to rolled EN AW-6082-T6 sheet metal", *International Journal of Fatigue,* vol. 140, 2020, p. 105805.

[Mos18] MostTech e.U., www.mosttech.at/3d-metalldruck/am-spannsystem/am-lock/. AM-Lock, Das Nullpunkt-Spann- und Positioniersystem für den 3D-Druck, 2018.

[Nor22] Norsk Titanium, The future of manufacturing is rapid plasma deposition®, https://www.norsktitanium.com/, 14.09.2022

[Sch19] SCHWARZ A., GEBHARDT A., SCHLESER M., POPOOLA P., "New Welding Joint Geometries Manufactured by Powder Bed Fusion from 316L", *Materials Performance and Characterization*, vol. 8 no. 6, 2019, p. 20180096.

[Sch21] SCHWARZ A., SCHLESER M., GERHARDS B., POPOOLA P., GEBHARDT A., "Welding of Additive Manufactured ALSI10MG: Using Laser Welding in a Vacuum for High Quality Weld Seams – A New Approach to Welding LPBF Manufactured ALSI10MG", *South African Journal of Industrial Engineering*, vol. 32 no. 4, 2021.

[Sef22] SEFENE E. M., HAILU Y. M., TSEGAW A. A., "Metal hybrid additive manufacturing: state-of-the-art", Progress in Additive Manufacturing, 2022.

[She19] SHEN C., LISS K.-D., REID M., PAN Z., MA Y., LI X., LI H., "In-situ neutron diffraction characterization on the phase evolution of γ-TiAl alloy during the wire-arc additive manufacturing process", *Journal of Alloys and Compounds,* vol. 778, 2019, p. 280-287.

[Tah17] TAHERI H., SHOAIB M. R. B. M., KOESTER L. W., BIGELOW T. A., COLLINS P. C., BOND L. J., „Powder-based additive manufacturing – a review of types of defects, generation mechanisms, detection, property evaluation and metrology", *International Journal of Additive and Subtractive Materials Manufacturing,* vol. 1 no. 2, 2017, p. 172.

[Tav18] TAVLOVICH B., SHRIZLY A., KATZ R., "EBW and LBW of Additive Manufactured Ti6Al4V Products", Welding Journal, vol. 97 no. 6, 2018, p. 179-190.

[Tre19] TREUTLER K., KAMPER S., LEICHER M., BICK T., WESLING V., "Multi-Material Design in Welding Arc Additive Manufacturing", *Metals*, vol. 9 no. 7, 2019, p. 809.

[Wan18] WANG J., PAN Z., MA Y., LU Y., SHEN C., CUIURI D., LI H., "Characterization of wire arc additively manufactured titanium aluminide functionally graded material: Microstructure, mechanical properties and oxidation behaviour", *Materials Science and Engineering: A*, vol. 734, 2018, p. 110-119.

[Wit15] Wits W. W., Becker J. J., "Laser Beam Welding of Titanium Additive Manufactured Parts", *Procedia CIRP*, vol. 28, 2015, p. 70-75.

[Wri22] WRIGHT I., www.engineering.com/deutsch/fertigung/hybridfertigung-die-zukunft-des-3d-drucks-in-der-produktion/, 2022.

[Yan19] YANG J., WANG Y., LI F., HUANG W., JING G., WANG Z., ZENG X., "Weldability, microstructure and mechanical properties of laser-welded selective laser melted 304 stainless steel joints", *Journal of Materials Science & Technology,* vol. 35 no. 9, 2019, p. 1817-1824.

[Yan20] YANG Z., LIU Q., WANG Y., MA Z., LIU Y., "Fabrication of multi-element alloys by twin wire arc additive manufacturing combined with in-situ alloying", *Materials Research Letters*, vol. 8 no. 12, 2020, p. 477-482.

[Zap20] ZAPF H., HÖFEMANN M., EMMELMANN C., "Laser welding of additively manufactured medium manganese steel alloy with conventionally manufactured dual-phase steel", *Procedia CIRP*, vol. 94, 2020, p. 655-660.

Imprint

Fraunhofer Research Institution for
Additive Manufacturing Technologies IAPT
Am Schleusengraben 14
21029 Hamburg-Bergedorf
Germany

Telephone +49 40 48 40 10-500
Fax +49 40 48 40 10-999
www.iapt.fraunhofer.de
info@iapt.fraunhofer.de

A legally dependent entity of
Fraunhofer-Gesellschaft zur Förderung
der angewandten Forschung e.V.
Hansastrasse 27c
80686 Munich
Germany
www.fraunhofer.de
info@zv.fraunhofer.de

Status of the Deep Dive, October 2022

Contact

Dr. Denise Loder
Head of Department Marketing & Communication
Telephone +49 40 48 40 10-508
eMail denise.loder@iapt.fraunhofer.de

Photo credits:
all image rights are held by Fraunhofer IAPT
except for Figure 5/6: DMG Moori [Dmg22],
Figure 7: Hybrid Manufacturing Technology [Hyb22]
Figure 8: Additive Production [Mat22],
Figure 22: Siemens [Gei22]. Figure 24: Mapal [Map20]
Figure 25: Norsk Titanium [Nor22]