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EVALUATING CONCEPTS FOR THE INTEGRATION OF MILLED COMPONENTS INTO THE ADDITIVE MANUFACTURING PROCESS

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Abstract

Laser Powder Bed Fusion (L-PBF) has specific advantages over conventional manufacturing processes. These include high freedom in the design of components and cost-efficient production of small quantities. However, the surface quality of components is low compared to milling and the production of large components is often associated with high costs. These challenges are addressed by integrating milled components into the L-PBF process. Therefore, various concepts are presented for positioning, aligning, and fastening machined components in the build space of the L-PBF system with the goal to provide a reliable way to start the L-PBF process on top of these components. Thus, allowing the potential of additive and subtractive manufacturing to be exploited without requiring an additional joining operation. Finally, these concepts are applied to a steering shaft bracket and the costs for manufacturing are evaluated. A 25% reduction in manufacturing costs was achieved compared to the purely additively manufactured component.

Introduction

Additive manufacturing offers great potential for geometric design through the layer-by-layer fabrication of components, thereby improving products in various applications. For example, the design freedom of additive manufacturing can be used to reduce mass and provide a more efficient use of a product for example by reducing fuel consumption [1]. An even greater reduction in mass is possible when multiple components are integrated into a single one. However, the complexity of the integrated component increases in terms of the number of geometric features and thus the manufacturing costs, due to a higher need for support structures, post-processing and longer production time [2]. In the context of Design for Additive Manufacturing (DfAM), there are already approaches for merging multiple components into one. The separation of components for additive manufacturing for example, to reduce the quantity of support structures or to manufacture components that exceed the building space, is discussed less frequently in the literature on DfAM [3]. The main approach of these contributions is to perform a methodical separation of components that exceed the build space of the additive manufacturing system and can subsequently be manufactured separately. However, component separation also allows the individual elements to be manufactured in different manufacturing processes, which will be referred to as hybrid manufacturing in the following discussion. In this way, the potential of both manufacturing processes can be profited from. A systematic procedure for the selection of components for hybrid manufacturing is presented in [4].

The advantages of additive manufacturing are the high geometric freedom and the ability to produce complex geometries while producing less waste. In addition, the dependency of the production costs regarding the number of components is significantly lower than with machining or casting processes [5]. This enables the individualization of components for each single customer. On the other hand, the surface quality of components is low compared to machining processes and leads to long cycle times and, especially in the field of metal additive manufacturing, high costs [1]. Machining processes such as milling, for example, have significantly different properties. Here, a precise, repeatable process leads to good surface quality. Productivity is also higher than in additive manufacturing, for example, due to the lower cycle times. However, due to the subtractive nature of these manufacturing processes, a large amount of waste is produced depending on the geometry. The costs are strongly dependent on the number of pieces to be produced and individualization is only possible with higher effort.

The combination of additive and subtractive manufacturing as shown in Figure 1 makes it possible to reduce costs and waste while improving surface quality in some areas. The prerequisite for this is the adaptation of the design of the individual parts and the selection of the manufacturing process that is more suitable for the part in question. Design guidelines that support the designer in the selection of parts for hybrid manufacturing and the design of these parts have already been addressed in the literature [4].

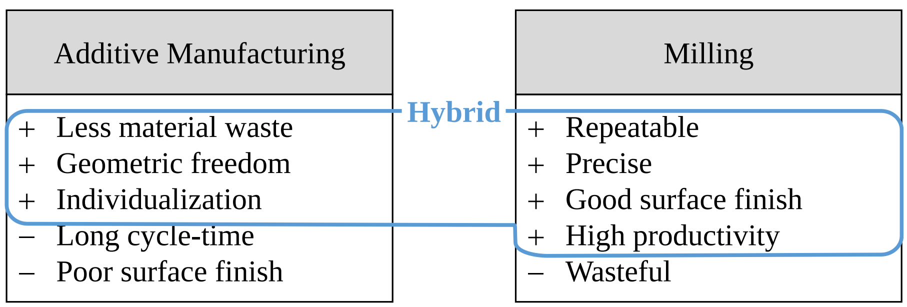


Figure 1: Properties of additive manufacturing and milling, based on [6]

A hybrid process, which combines the advantages of both processes and simultaneously cancels out the disadvantages, therefore seems beneficial. In addition, different materials comprising various properties can be bonded together. For example, combinations of aluminum and titanium [7], aluminum and steel [8], and steel and copper [9] have already been investigated and have in some cases produced good results. In this way, potentials can be exploited that cannot be achieved either with additive manufacturing or with subtractive manufacturing alone. While a combination of additive manufacturing with other manufacturing processes is also conceivable, this contribution is limited to the consideration of milling and additive manufacturing using L-PBF. There are a few examples in literature in which milled components have been inserted into the build space [10]. However, concepts for integration have not yet been developed systematically and a methodical comparison of the different solutions is missing.

Concepts for the Integration of Milled Components

As part of the development of new concepts, the function of inserting components into the build space of the additive manufacturing system is first divided into sub-functions. These sub-functions are placement, orientation and fastening of the components. According to Figure 2, the placement of the components corresponds to the x and y coordinates and the rotation around the z-axis. The placement is necessary so that the additively manufactured part of the component is built up at the correct position on the top of the milled component and no offset occurs between the two parts. The orientation describes the rotation of the part around the x- and y-axes. It is necessary to ensure parallelism between the recoater of the manufacturing system and the inserted component. Thus, at the start of the additive manufacturing process, a uniform first powder layer is achieved on top of the milled part. This is an important parameter for a solid fusion of the additively manufactured part to the milled component and thus a mechanically durable connection. Finally, it is often necessary to fasten the inserted components, since thermal expansion during exposure or contact with the coater can lead to displacement of the component during the additive manufacturing process.

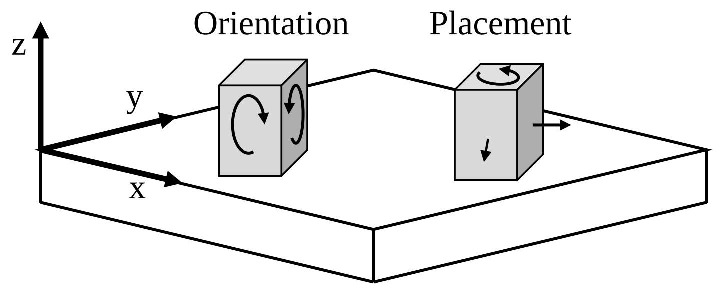


Figure 2: Orientation and placement of the components on the build plate.

The three sub-functions can be solved almost independently of each other. Different concepts for each of these sub-functions are therefore presented below. The solutions for the sub-functions are then combined to several overall concepts. Finally, the various concepts are evaluated in terms of the integration effort required for one-off production and repeated production of the same component, and in terms of their suitability for the production of small and large components.

Placement

The placement of the milled components is important to avoid misalignment of the two differently manufactured parts. There are two basic options for placement: Machining the build platform so that the milled components can be inserted, as shown in Figure 3 a). The second option is the additive manufacturing of fixtures for positioning the components directly on the build platform (see Figure 3 b)). The machining of the build platform is initially more complex, but leads to a better fit and can be reused for the same component. For high volumes, the machining of the build platform is therefore preferable. If only small quantities are required, additively manufactured mounts are more suitable, as the build platform can also be reused for other components afterwards.

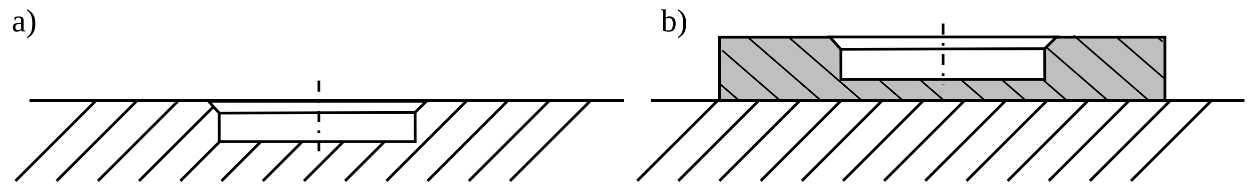


Figure 3: Concepts for placing milled parts into the additive manufacturing process with a) machined build platform insertion area and b) additive manufactured fixture to be placed on top of build platform.

Orientation

In addition to the placement of the milled components in the build space of the additive manufacturing system, an orientation of the components must also take place. The goal of this orientation is to ensure the surface on which the additive manufacturing process is started and the coater of the manufacturing system are parallel. Lack of parallelism between the component and the coater can lead to an uneven first powder layer and thus possibly to poor bonding, and to an angular misalignment within the component. Therefore, the alignment of the inserted milled parts is mandatory to achieve good quality.

Some machines are adjustable to perform this orientation for the build platform and thus also for the milled parts mounted on it. If this option is not available, care must be taken to ensure parallelism between the coater and the component when inserting the milled parts. Overall, the orientation of the components is still a challenge because the additive manufacturing systems currently available on the market are not designed for inserting milled components. This means that a complex manual alignment of the individual components is required, especially in the case of multiple components.

Fastening

Once the part has been placed and oriented in the build space, the part must be fastened in the current position. Form-fit, force-fit or material-fit principles can be used for fastening. Material bonds include adhesive or welded joints. The latter are excluded in advance due to the destructive detachability of the connection. As shown in Figure 4 a) adhesive bonds are possible, but the temperature resistance must be checked when selecting the adhesive. Depending on the adhesive, the advantage of adhesive bonding can be improved heat conduction from the milled component to the building platform. Disadvantages can arise from mixing the adhesive and unmelted powder. For example, adhesive residues must be conscientiously removed after the additive manufacturing process. In addition, the component must be freed from adhesive residues and cleaned.

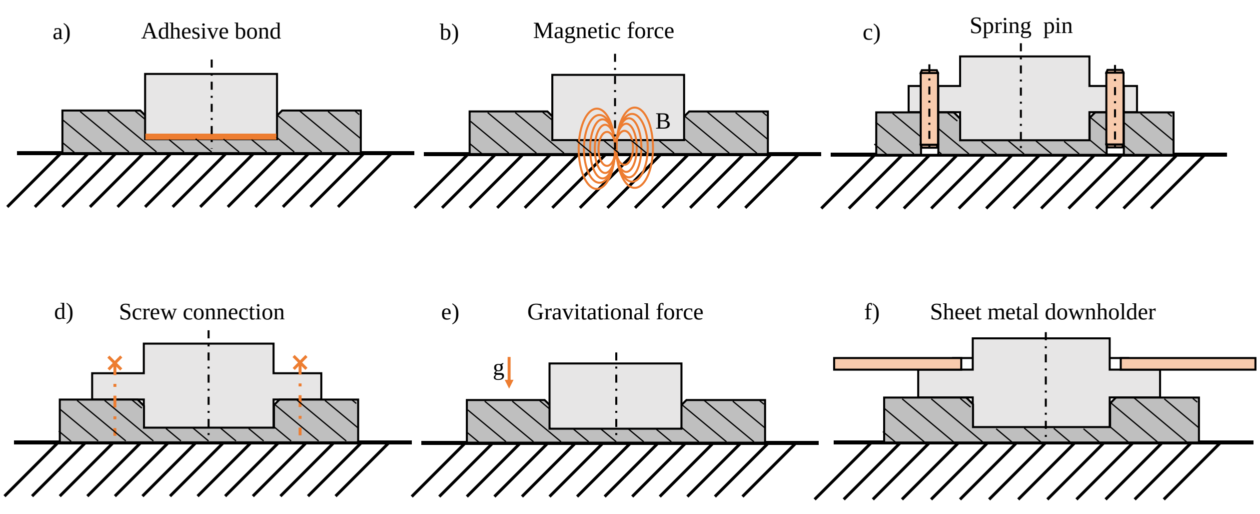


Figure 4: Concepts for fastening milled parts in the additive manufacturing process.

Force-fit connections include frictional connections and magnetic connections (see Figure 4 b)). An example of a frictional connection by means of a longitudinally slotted spring pin is shown in Figure 4 c). For this purpose, holes must be provided in the holder and in the milled part itself into which the spring pin is inserted. In the relaxed state, the spring pin has a larger diameter than the diameter of the bore. In the assembled state, the expansion of the pin causes a frictional force on the outer diameter, which connects the components to each other. The use of magnets requires a magnetic material, but also results in a magnetic attraction of the powder. This solution is therefore particularly suitable when a magnetic milled part is processed with a non-magnetic powder.

An intermediate solution between force and form-fit connections is the screw connection as shown in Figure 4 d). This also requires holes in the milled part and a threaded hole in the fixture. The advantage of the screw connection is that it can be easily disassembled after the manufacturing process, and the force with which the component is fastened can be adjusted. The disadvantage is the necessity to modify the milled part. Particularly for small components where low thermal distortion is to be expected, fastening can be dispensed completely if necessary. The insertion of the milled semi-finished products into the holders and the weight force are then sufficient to prevent displacement during the manufacturing process as shown in Figure 4 e). In particular, if many components are to be inserted, a metal sheet can be used as a hold-down device, as shown in Figure 4 f). The advantage is that many components can be fixed at once. In addition, the individual components do not have to be adapted and, for example, there is no need to drill a hole in the components. Furthermore, the powder can be spread only on top of the hold-down sheet, so that less powder is required to fill the build space to the first layer of the L-PBF process. The disadvantage is that it is necessary to manufacture a suitable metal sheet to serve as a hold-down device. This solution is therefore particularly suitable for the production of a large number of components.

The various concepts offered differ in terms of the effort required to integrate milled components and the strength of the fastening of the components. These two criteria are therefore used to evaluate the concepts. In addition, a distinction must be made between the one-time effort, such as manipulation of the building platform, and a recurring effort, such as the application of an adhesive bond. Finally, this leads to an evaluation of the quantities for which the respective concept is suitable. For large quantities, a high one-time effort can be accepted, whereas for smaller quantities, a lower recurring effort should be preferred.

The second criterion is the strength of the attachment of the components to the building platform. For example, a bolted connection can transmit more force than an adhesive connection. The strength of the connection is particularly relevant for components that are expected to have a large thermal distortion. The warpage of the components can cause the components to move out of the mount. In addition, the warpage can cause the coater to collide with the component when applying new material, thus exerting a force on the component. The fixture must then be strong enough to hold the component in place. Thermal distortion occurs in particular with large exposed areas, i.e. when the components comprise a large volume. Accordingly, the different concepts can be evaluated on the basis of the size of the components.

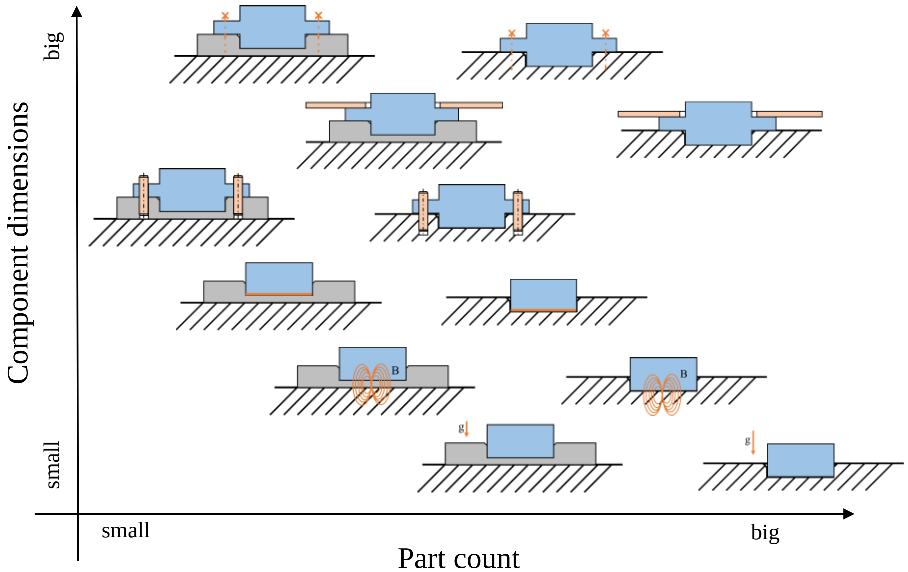


Figure 5: Comparison of the different concepts for integration of milled parts in the additive manufacturing process according to parts size and part count of a production run.

Evaluation

The concepts developed above are evaluated here using an exemplary component from a racing vehicle. The component selected for additive manufacturing is the vehicle's steering shaft bracket. This is bolted to the carbon-fiber-reinforced polymer body and includes two roller bearings that hold the steering shaft. Accordingly, some requirements are placed on the steering shaft bracket. For example, the component should be as light as possible, whereby the angular deviation of the steering shaft in operation must not exceed 0.4°. To meet these requirements, a topology optimization of the component was carried out to achieve the required stiffness with minimum mass. The resulting complex structure is particularly well suited for additive manufacturing, especially since the steering shaft bracket is only produced in small quantities. The geometry of the component is not limited by restrictions of the manufacturing processes but can be designed to suit the lightweight design based on the load.

In contrast, however, there are requirements for the two bearing seats of the component. Here, good surface quality with low tolerance is necessary to ensure the assembly and reliable operation of the bearings. These requirements cannot be met by additive manufacturing using L-PBF. In the previous approach, this meant that the additively manufactured components had to be reworked using machining processes in order to be able to produce the bearing seats in the corresponding quality. Here, as shown in Figure 6 the component is separated into two parts and one is manufactured additively and the other by machining. The lower part, which contains the bearing seats, is produced by milling, while the topology-optimized structure is produced additively. The two components are joined during the additive manufacturing process, which starts on top of the machined component.

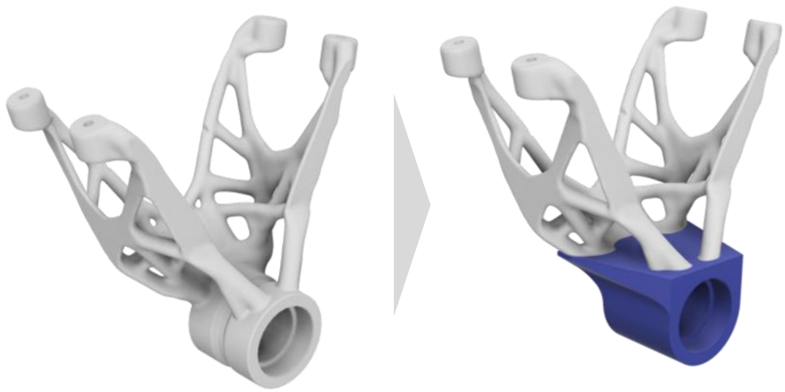
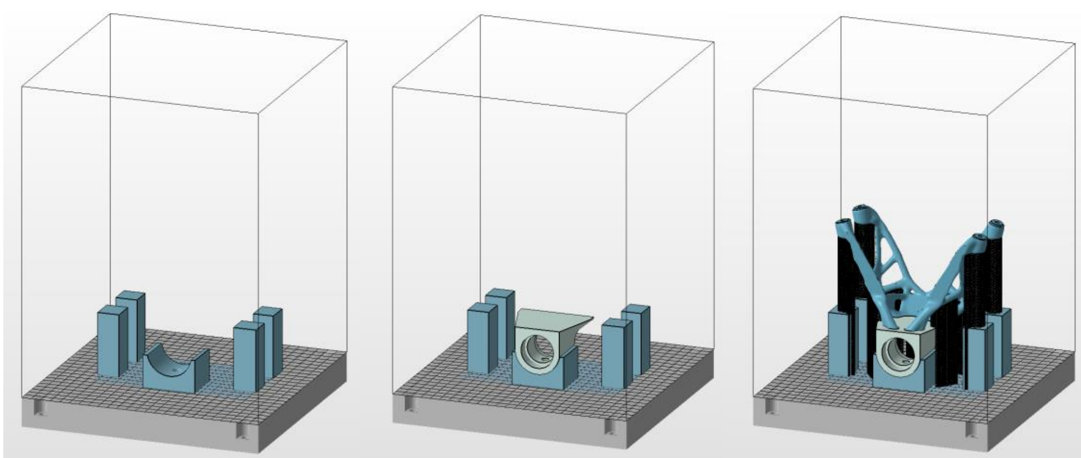


Figure 6: Separation of the steering shaft bracket into a milled part (blue) and an additively manufactured part.

The steering shaft bracket is separated using a plane. This surface later forms the base surface for the start of the additive manufacturing process. The steering shaft bracket is only manufactured in small quantities. Manipulating the build platform is therefore time-consuming and means that the build platform cannot be reused for other components. The milled component is aligned by means of an additively manufactured structure that represents the negative of the geometry of the bearing seats. For fastening the milled part of the steering shaft bracket, a clamping connection was first provided by means of a spring pin. For this purpose, a hole is provided in the milled part and the additively manufactured fixture, the spring pin is then first fastened in the milled part and then in the additively manufactured fixture when the component is inserted. However, during the first test, the inserted part was moved by contact with the coater, so the manufacturing process had to be aborted. The fastening force by the spring pin is accordingly too low, so the design of the fixture was changed to a screw connection instead.



1. Additive manufacturing of the fixtures	2. Inserting, orienting, and fixing the milled part	3. Additive manufacturing of the remaining part

Figure 7: Concept for integrating milled parts into the additive manufacturing process.

Figure 7 shows the planned procedure for integrating a milled component into the additive manufacturing process. First, the fixtures are additively manufactured directly on the build platform, which is then used to place, orient, and fasten the milled part, which is inserted in the second step. Finally, another additive manufacturing process is started on the flat upper side of the milled part, in which the remaining part of the component is then placed directly on the milled part.

Figure 8 shows the steps of the realized manufacturing process. After the fixtures have been manufactured, the unfused powder must be at least partially removed from the build space of the additive manufacturing system (see Figure 8 a)). This then allows the insertion of the milled part. Figure 8 b) shows the fastening of the milled part by means of a screw connection in the build space of the system. Before the part is fixed, the surface must be aligned parallel to the recoater of the manufacturing system. The success of the alignment can be seen from the uniformly thin layer of powder on the top of the milled part in Figure 8 c).

a) b) c)

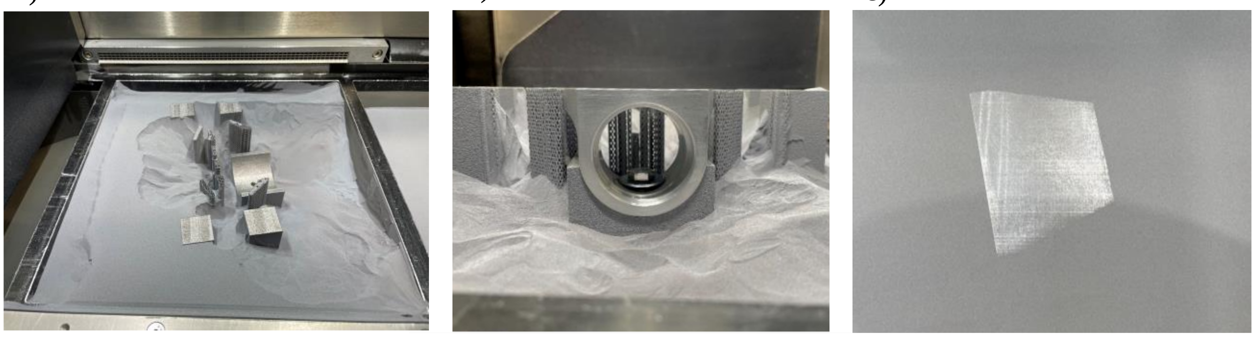


Figure 8: Integration of a milled part into the additive manufacturing process.

The final result of the hybrid manufacturing process is shown in Figure 9. The steering shaft bracket comprises the topology-optimized, additively manufactured structure and the milled bearing seats, which can be used without any further post-processing. Table 1 also shows the costs for hybrid production in comparison with purely additive manufacturing of the steering shaft bracket. By inserting a milled component, the costs were reduced by 25 %.

a) b)

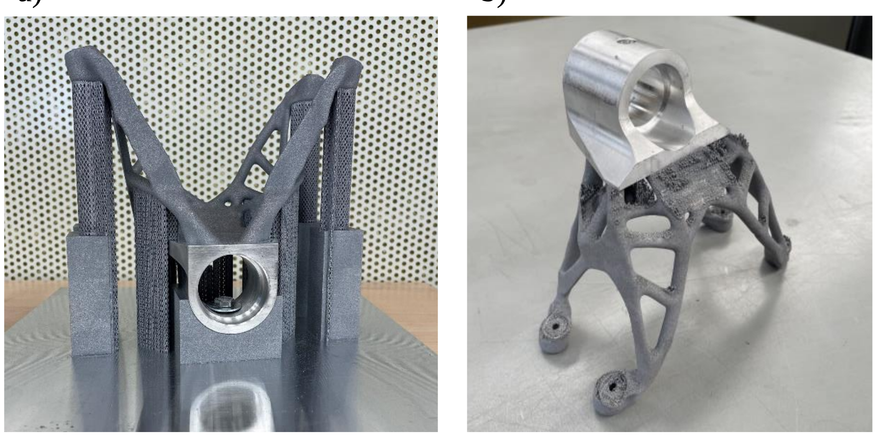


Figure 9: Final hybrid manufactured steering shaft bracket.

Table 1: Comparison of the cost of additive manufacturing of the steering shaft bracket with hybrid manufacturing.

	Additive manufacturing	Hybrid manufacturing
Additive manufacturing process	1,400 €	909 €
Milling process	-	137 €
Rework of the bearing seats	46 €	-
Sum	**1,446 €**	**1,046 €**

Summary and Outlook

In summary, several concepts for the integration of machined components into the additive manufacturing process were developed and compared to each other with regard to the size of the components and the number of pieces to be manufactured. This enables to systematically select a suitable concept for the respective application. Two of these concepts were also applied to an example component, the steering shaft bracket of a racing car. It was shown that a frictional connection using a spring pin could not absorb sufficiently high forces, which is why a screw connection was used in a second step. This enabled the successful hybrid production of the steering shaft bracket. A comparison of the costs also showed that hybrid production is 25% cheaper than pure additive manufacturing. This can be attributed in particular to the reduced expense for reworking the bearing seats.

The orientation of the milled components is particularly challenging, as this currently requires manual intervention by the operator. Further concepts can be developed here in the future, but these will require to adapt the additive manufacturing system. The next steps are also the investigation of different material combinations, as well as the investigation of the mechanical load capacity of the connection zone.

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