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CLAMPING CONCEPT FOR 6 SIDE HYBRID MANUFACTURING

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Abstract

For most technical applications, the surface quality and tolerances that result directly from additive processes are not suitable. Hybrid manufacturing as a combination of additive and subtractive manufacturing process steps can help solving this issue. In this work, a conceptional adjustable cast clamping process is introduced for a combination of Laser-based Powder-Bed-Fusion (LPBF) and milling. For component clamping during the milling process, the components are cast in place with a low-melting metal alloy, creating form-fit and force-fit connection. To prove the applicability, a rough estimation of occurring milling forces was conducted. In a subsequent series of tests, validation of clamping force was carried out using complex part geometries. A prototype fixture designed for this cast clamping process has been developed and tested. This fixture allows complex non-restricted 6-side machining of parts without moving it relative to the fixture or the need of any additional manual rework on part surfaces.

Keywords: flexible clamping concept, 6-side machining, hybrid manufacturing

Introduction

The development of complex and sophisticated products demands continuously improving manufacturing processes. Multiple factors can be relevant for the competitiveness and efficiency of a product during its lifecycle. The requirements for the product usually have conflicting goals. Customers demand for a tailored and technically mature product to satisfy the exact individual requirement, but for reasonable cost [1]. These conflicting goals are motivation for efficient manufacturing processes. In this work hybrid manufacturing is defined as a process combination of an additive and a subtractive process step. With a hybrid manufacturing process, it is possible to meet individual customer needs and create a valuable business case staring at a lot size of one.
Hybrid manufacturing has been long recognized and is embodied in the availability of hybrid manufacturing systems with combined additive and subtractive capabilities to produce not only complex but also precise parts. It can increase the flexibility of the manufacturing process and reduce the amount of used material [2, 3, 4, 5]. The additive process step generates a semi-finished product, where the subtractive process step adds function and precision, e.g., geometrical accuracy and surface finish to the part where it is needed. The combination of a near net shape additive and subtractive manufacturing can reduce material and tool costs as well as overall machine time, resulting in cost advantages. However, combining two manufacturing process steps leads to the disadvantage of limited part design of both manufacturing methods. Machine processes are usually restricted to 5-side machining. A true 6-side machining is not possible without unclamping the part and clamp it in a new position after first machining steps. After the re-clamping process, the parts usually must be repositioned and its position calibrated in order to minimize any possible error in rotation and translation with respect to the machine coordinate system. Especially for components with complex geometries, a lot size one and the size of dental products like crowns or bridges this re-clamping process is time consuming. Alternatives are custom-made clamping devices, e.g., negative clamping jaws, which, however, cause considerable additional costs for lot size one due to the individual manufacturing. These limitations inhibit a fully automated production process. Common flexible clamping methods, like vacuum clamping (mostly for flat surfaces), clamping with formed clamping jaws

or clamping with frozen fluids (thin layer of liquid on a flat freeze plate), already exists with the goal to solve this issue [6, 7, 8, 9]. However, none of these clamping methods are suitable for automated 6-side machining and handling of parts completely defined by free-form surfaces, like dental products. Depending on the geometrical shape, tools cannot reach every part surface and the lack of geometric reference during re-clamping challenges the position re-calibrating process.

A promising approach shows a clamping by a low-melting metal alloy, though the most common used alloy contains Cadmium [10, 11, 12]. Acute inhalation of airborne Cd, e.g. from soldering or welding fumes, can cause severe chemical pneumonitis. Long-term exposure to low air concentrations can lead to chronic lung disease and possibly lung cancer. Long-term excessive exposure from air or food causes renal tubular dysfunction. In the case of oral intake, amounts as low as 300µg daily over a prolonged period are sufficient for chronic poisoning symptoms such as Itai-Itai disease [13, 14]. The acceptance in medicine and medical technology for toxic substances in the production environment is not present, even if it is only an auxiliary substance during production.

The focus of this work is an adjusted clamping process chain using low melting alloy for mechanical 6-side postprocessing of via L-PBF additively manufactured parts. A proof of concept shows whether the clamping forces can be sufficiently absorbed during milling and whether components can be machined completely from 6 sides with sufficient accuracy.

Clamping Concept

The clamping concept developed in this work for the post-processing of components manufactured by means of L-PBF uses a Cadmium free liquified low melting metal alloy to clamp the part by cast clamping. The process was designed for the hybrid production of dental products such as crowns, bridges and abutments. In addition to a lot size of one and a small part size of about 15x12x12 mm³, dental products are characterized by a complete freeform surface, hence complicating an automated manufacturing process. Therefore, a process chain and a clamping concept was needed which combines geometrical flexibility, the flexible handling and clamping of small and complex shaped parts.

A process chain was designed (Figure 1) using low melting alloy as clamping mechanism that enables a mechanical postprocessing of all 6 sides without losing the relative component position and orientation inside the milling machine until the part is finished from all sides. A clamping device (CD) that enables the handling of the part, the building platform, the casting process and the process of separation of part and building platform is implemented in the process chain.

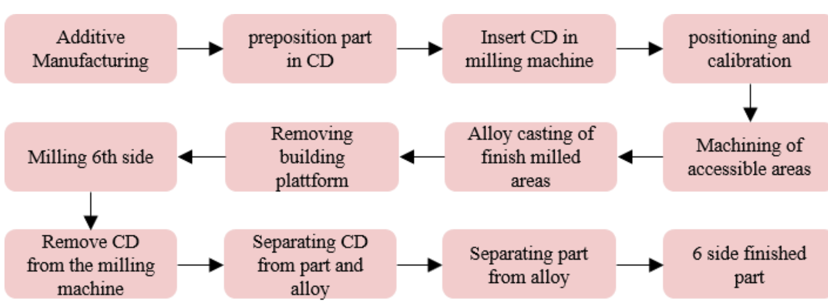

Figure 1: Process chain for hybrid manufacturing with low melting alloy as part of the CD

Freeze clamping shows its flexibility due to the flat geometry of a freeze clamping plate when components show flat surface areas or many contact areas to the surface of the freeze clamping plate. In addition, due to the passive cooling of the component, thermal expansion or shrinkage must be considered and compensated if necessary. In casting clamping, the area of the component surrounded by the casting medium is made dependent on the casting height. This gives greater flexibility in positioning the component. The machining process takes place at room temperature.

Development of a clamping device for 6-side machining

For a fully capable 6-side clamping concept a clamping device is designed and the previously described process chain (Figure 1) is adjusted to necessary process steps [15]. The CD is shown in Figure 2. The base mount (1) is the center component of the CD. The part (2) is connected via support structures on a building platform (3). This building platform is pre-located and fixed by a rubber ring (4) and a mounting ring (5) to the base mount.
A sensor (6) for measuring the poured liquid level height was integrated to the base mount. The system is completed with a cavity cover (7), which forms the bottom cavity for the alloy casting. The base mount is directly screwed on a zero-point clamping system Polygrip Erowa ITS50 (not shown in Figure 2) that is used in the used 5-axis CNC mill Datron C5.

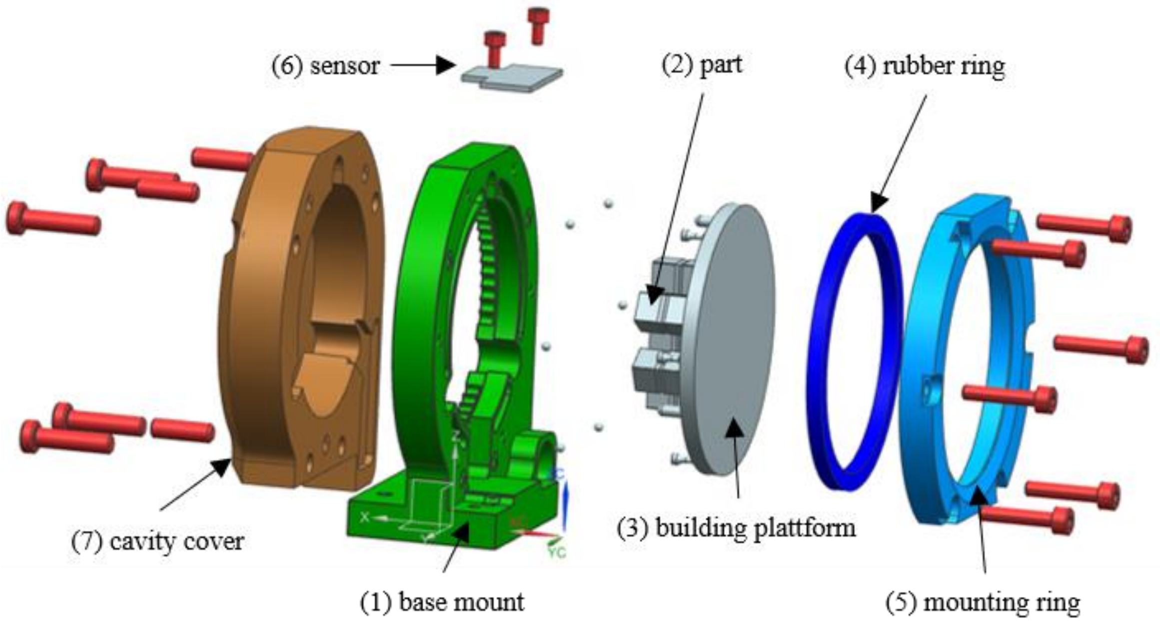

Figure 2: Exploded drawing of the CD

Due to the importance of the casting operation in the process, the CD was designed with geometries necessary for casting. In this context, the calculation values and methods commonly used in casting technology for widely used ferrous and non-ferrous metals could only be used to a limited extent for the design of an in-bi alloy casting process, since no material parameters are available here. Casting diameter (12 mm), casting channel (1.128 cm²) and gate (0.7 cm²) were estimated according to table values for small components [16].

Properties of clamping metal alloy

The following clamping concept uses a metal alloy with a melting point below 100°C. Therefore, the alloy can be liquified in hot water. A requirement for the alloy is a negative coefficient of thermal expansion (CTE) which results in an expansion after change of phase from liquid to solid state. Also clamping forces should not be lost over time, as it happens for example with base-, safe- or mellottes-alloy [17].
An Indium-Bismuth alloy (66 % / 34 % weight ratio) with a melting point of 72,4°C was chosen for the following experiments after a preliminary investigation [18]. Furthermore, this alloy exhibits the necessary negative CET after solidifying. Preliminary experiments showed low viscosity, good mold filling behavior and a low tendency to slag formation. However, for the chosen alloy due to its lack of application, no data was found to describe the mechanical or thermal properties. The phase diagram is not fully confirmed and shows differences in the alpha and beta phase depending on the literature [19, 20]. Since only a eutectic alloy was used for the following

experiments, these differences have no consequence. Material properties, like expansion/shrinkage over time and poisson's ratio have to be determined.

Experimental setup

In preliminary tests to measure the clamping force of the low-melting alloy, it was proven that the shear force load represents the critical case. The comparative force whose load the system has to withstand was chosen from a manufacturing process of dental products. Conventional machining of dental crowns was chosen as the comparative process. In this process, machining with a 3 mm solid carbide ball endmill is identified as the biggest tool. The specific cutting force is determined according to Kienzle and Victor and amounts to 16.4 N [21].
Seven test specimens are arranged on the build platform. One is centered on the build platform. Six others are arranged at radius 16 mm and at 60° intervals around the central specimen. The distances were chosen so that there is sufficient safety distance to other specimens and the CD when using a 3mm ball endmill. The specimens are each cuboid with the dimensions 8x8x14 mm³ and have a 4 mm hole centrically along the Z axis. At a height of 7 mm, the test specimens have a circumferential notch which serves as a filling level for the casting process (Figure 3).
The state after additive manufacturing and before mechanical postprocessing is the starting point. The specimen made of stainless steel AISI 316L (1.4404) is thoroughly cleaned and then measured on a Leitz PMM864 tactile coordinate measuring machine with a measurement deviation of 1.2+L/300µm (i.e., 1.4µm measurement deviation for a pitch circle diameter of approx. 60mm) at previously defined points with a ruby touch ball with the diameter of 1,5 mm (Figure 3).

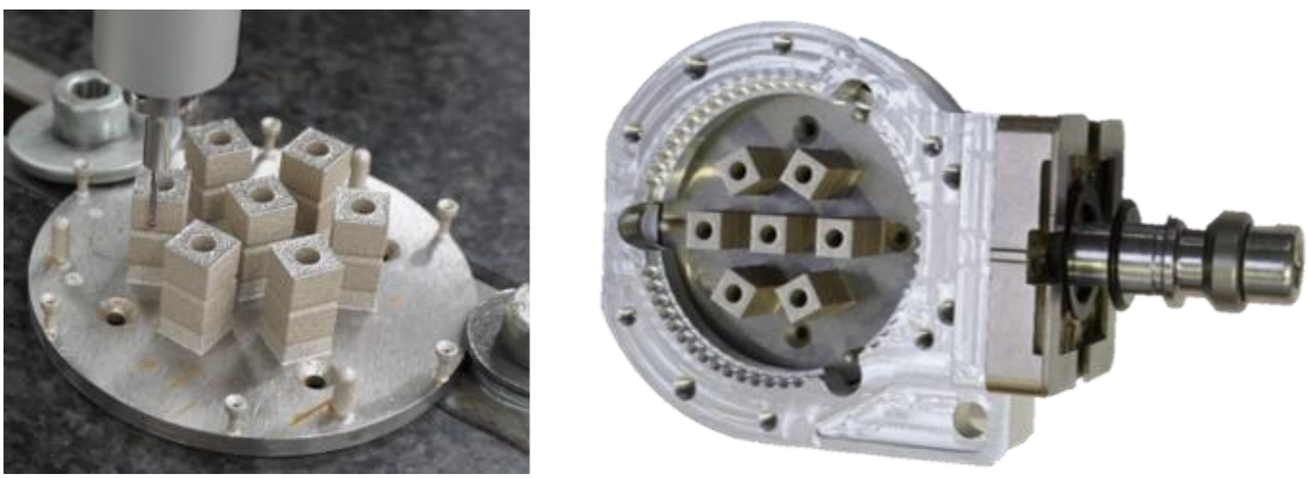

Figure 3: Left: measurement on a coordinate measuring machine; right: part on building platform inserted in CD

The measurement of the specimen was carried out over the processing steps along the process chain:

- not clamped, as build,
- clamped, as build,
- clamped, front side machined, component cast in, building platform separated.

The calibration pins serve as reference points during the measurements on the front side until the casting process. The Pins are measured with 100 touches on the lateral side and 104 touches on the hemisphere. On each specimen, 100 touches of the drilling axis and 30 touches for each wall surface were performed to determine orientation and position. After the casting process and separation of the build platform, the same number of touches was performed from the rear side.
L-PBF semi-finished products are subject to production-related tolerances. In addition, the alignment of the specimens via the additively manufactured conical prepositioning pins can only be evaluated as a very rough component positioning. The specimens are measured indirectly within the milling machine via the calibration pins (Figure 4). The minimum machining oversize required must be determined experimentally to ensure the

removal of all additive surfaces and thus geometric precision and surface quality of the milling process. Therefore, specimens with dimensions increasing in 50 µm steps, in the range 0 µm to 300µm, were manufactured.

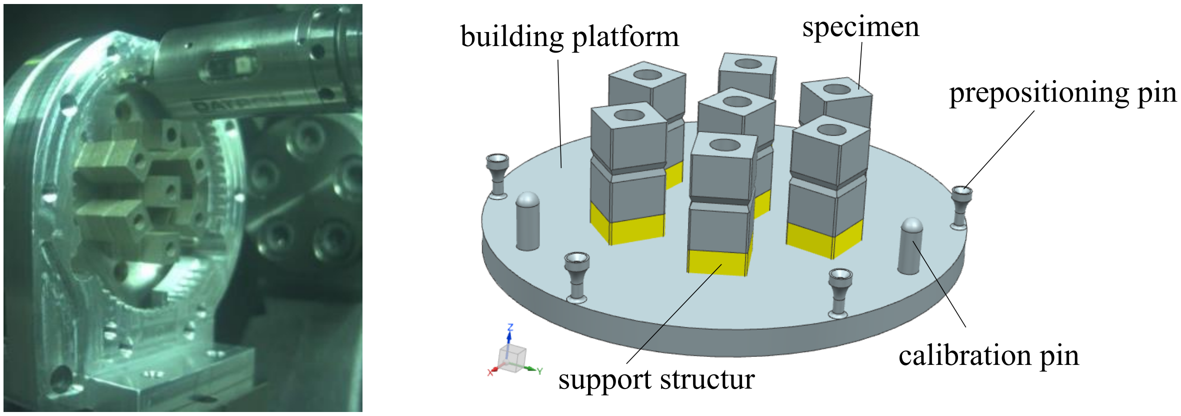

Figure 4: Left: calibration process in Datron C5; right: CD CAD visualisation

The machining process is divided into two different machining strategies:

1. Machining of all external surfaces of the specimen with oversize in 50µm increments from 0-300µm compared to the targeted geometry. Each side of the specimens is milled to half the specimen height. Where the bore has been milled directly to the internal diameter of 4 mm on all specimens to allow tactile measurement.
2. Machining from the front beyond half the specimen height to a depth of 9 mm to get two machined surfaces on butt from both sides. The machining oversize has also been increased in 50µm steps in a range from 0 to 300 µm. The holes are milled equal to strategy one.

After machining the front side, the CD is removed from the machine, the cavity cover is attached, and the specimens are cast in. After the alloy has cooled, the rubber and mounting ring are removed. The support structures, positions and calibration pins are manually sawed off with minimal force. The clamping device opened from the back is shown in Figure 5. The CD is inserted back into the machine and the now revealed sixth side is now finish machined. The CD with the finished specimens is then removed from the machine.

The specimens are heated to separate them from the alloy. The separated specimens are then cleaned from the alloy residues in an 80°C ultrasonic bath for 5 minutes. The height of the specimens is then measured using a dial gauge and compared with the height of the ideal geometry. Since there is no reference possibility in Z-axis after the casting and separation from the building platform, the height of the finished specimen plays a key role and can only be measured after the whole process is finished, including the separation from the alloy.

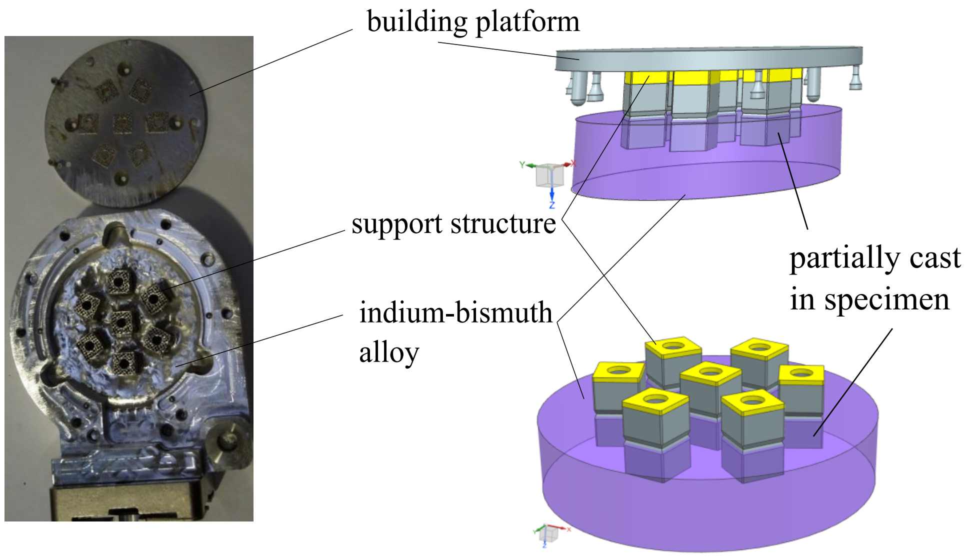

Figure 5: Left: exposed specimens with partially left support structure; right: CD CAD visualization before (top) and after the separation of specimens and building platform (bottom) as of the starting point for machine finishing of the 6th side

Results and Discussion

The experiment of the positioning accuracy has been carried out on one specimen within the scope of this work and is therefore only intended to provide a basic estimate of errors in the positioning accuracy of specimens along the process chain of a casting clamping system. The measured values for the angular deviation and displacement are shown in Table 1. Specimens with an oversize bigger than 150 µm were milled completely without any as build surface from the additive manufacturing process left.

Table 1: Averaged displacements and rotation along the process chain

Parameters	**Not clamped, as build**	**Clamped, as build**	**After removal of the building platform, 6th side not machined**
Angular rotation	0.0983°	0.0939°	1.305°
Displacement x	0.0137 mm	0.0136 mm	0.0422 mm
Displacement y	0.0040 mm	0.0026 mm	0.0129 mm
Displacement z	0.0006 mm	0.0004 mm	0.0012 mm

The measurement of the specimen heights after finish machining are shown in Table 2 with the used oversize. The results and deviation shown in Table 1 and Table 2 are sufficient to manufacture technical parts after general tolerance (± 0,1 mm) [22]. The deviation in Table 2 is a combination of the deviation of the CD, the zero-point clamping system and the machine repeatability. Also, it is not clear what part of the deviation of the CD is caused by the alloy behavior or a possible lack of stiffness of the CD itself. To determine the CD deviation, further experiments need to be executed.

Table 2: Measured component heights and average deviation

	Test series						
Oversize	**1**	**2**	**3**	**4**	**average**	**target**	**average deviation**
0 µm	14.249 mm	14.231 mm	14.263 mm	14.231 mm	14.244 mm	14.3 mm	0.056 mm
50 µm	14.155 mm	14.090 mm	14.079 mm	14.095 mm	14.105 mm	14.2 mm	0.095 mm
100 µm	14.063 mm	14.065 mm	14.074 mm	14.055 mm	14.064 mm	14.1 mm	0.036 mm
150 µm	14.018 mm	14.014 mm	14.060 mm	14.004 mm	14.024 mm	14.0 mm	0.024 mm
200 µm	13.794 mm	13.798 mm	13.852 mm	13.922 mm	13.842 mm	13.9 mm	0.059 mm
250 µm	13.802 mm	13.748 mm	13.764 mm	13.817 mm	13.783 mm	13.8 mm	0.017 mm
300 µm	13.655 mm	13.634 mm	13.638 mm	13.656 mm	13.646 mm	13.7 mm	0.054 mm

When measuring the specimens in the coordinate measuring machine, it has been shown that clamping the building platform (without casting) has no noticeable effect on the specimen position. It should be noted, however, larger components have higher thermal stresses that can lead to distortion during the process, in particular during the separation of the components and the building platform.
Measuring the specimens from the rear side has proved difficult because chips, support structures and the alloy melt can hinder tactile measurement (Figure 5). In addition, no reference geometry can be manufactured in the Z-direction, so that the component position can only be determined roughly from the rear side.
The measurements have shown that the handling with the cast clamping system has the potential to be uncritical for accuracy in the process. However, an angular average deviation of approx. 1.3° of the specimens at the seven measured rectangular structures can be considered small (considering the component dimension of 8x8x14 mm³ and the small measuring depth of 5 mm), since the rough additive manufactured component surface and the small measuring depth can lead to larger deviations in the measurements.
The casting process was carried out manually during the preliminary and main tests. A stable process, e.g., through automation, can increase the quality of the casting process. Nevertheless, all samples showed that the casting height of the solidified alloy even within a specimen sometimes fluctuates. It needs to be clarified whether an improvement can be achieved here through targeted heat management, e.g., in the form of fixed heating and cooling curves.
In addition, the specimens showed a consistent improvement in the surface finish at each 50µm oversize machining step. A completely bright machined surface was achieved with a selected allowance of 150µm. There was no noticeable offset at the abutting surfaces. No deviations were visually detected in the boreholes either.
The finished specimens could be easily separated from the clamping alloy afterwards. Examinations under an SEM showed that all residues of the casting material could be removed through an 80 °C ultrasonic water bath.
A critical point is the removal process of the building platform. The clamping forces of the alloy are limited, but not known due to unknown mechanical and thermal material properties. Therefore, the widely used hacksaw machine for separating additively manufactured components and building platform cannot be used here, as the clamping forces would be exceeded. Nevertheless, there are approaches to keep the forces low by means of a suitable support structure or the usage of a torque-controlled saw.

Conclusion and outlook

Within the scope of this work, a highly advanced clamping process and a clamping device tailored for hybrid manufacturing of complex part geometries and small lot sizes enabling automated 6-side machining is shown. The proof of concept was successfully made. It is shown that clamping forces during milling can be sufficiently absorbed, and components can be completely machined from 6 sides with a maximum absolute deviation to the desired net-shape of less than 0,06 mm. However, the effect of the stiffness of the conical prepositioning pin structures used in this context may have to be investigated in further work.

The optimization of the process chain and the clamping device has potential to minimize the occurring deviation and will be further investigated. Validating the limits of the process steps in the process chain as well as scaling would be a further step towards the mass adoption of additive manufacturing for lot size one technical components. The integration of all these different individual processes into one machine also poses a challenge under an economic point of view.
Both the process chain and the CD are not limited to the L-PBF process used here. An application of other additive manufacturing processes with building platforms will be investigated. Also, a limitation to metal parts needs to be revisited. For other materials like high performance polymers (e.g. PEEK), the temperature of 80°C of this process must be uncritical.

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