Development of a substrate unit for LPBF to increase automatization in manufacturing process chains

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Abstract
Additive processes enable a flexible production of individual and complex formed components. Particularly in the manufacturing of individually adapted components, such as in medical technology, or for complex shaped components, such as in the turbo industry, reworking on conventional machines is necessary to reach the technological requirements in terms of surface quality and shape tolerances. However, the more complicated the geometric shape of the component is, the more complex the referencing and clamping on conventional machines becomes. New clamping systems are necessary for individual components, which can take several weeks to manufacture so that the degree of automation within the production process chain decreases.

The paper presents a novel substrate unit, which allows the components to be produced additively on connecting elements. Compared to the conventional substrate plate, only the connecting elements are consumables, which enables the substrate unit itself to be used as a carrier clamping system through the process chain over a zero-point clamping system. The components can be removed from the substrate plate using a simple release mechanism. The degree of automation can be increased within the process chain.

Additive Manufacturing, LPBF, Clamping, Referencing, Process Chain, Substrate Plate, Post Processing, Automation, Milling

1. Introduction and problem definition
LPBF generated components are semi-finished products for many industries, such as the turbomachinery industry or the medical sector, which require further processing by subtractive machining up to the finished part to reach the technological requirements in terms of e.g. surface quality and shape tolerances. The reliable clamping and referencing of workpieces is of great importance in conventional machining in order to achieve the technological goals.[1]

The LPBF process offers a high degree of flexibility in the geometry design of the workpieces, without the need of tools or moulds. However, each LPBF generated component requires its own clamping and referencing concept on conventional machine tools for the finishing operation, which can also cope with shape deviations. Here, the design freedom of LPBF workpieces leads to a big challenge.

In principle, workpieces can be pre-positioned directly for conventional machining using locator elements [2]. The printed workpiece initially does not provide referencing surfaces on the LPBF workpiece (see Figure 1, left). The machining of these precise surfaces often requires its own fixture and several re-clamping processes. The development and manufacturing of the required adapted clamping system can take several weeks. The other possibility is to clamp the LPBF workpiece with a flexible clamping system such as a matrix clamping system and reference the LPBF workpiece with a position measurement directly in the machine (see Figure 1, centre) [3]. This possibility is time-intensive due to the necessary measurements and due to adaptation of the machine NC paths with Best-Fit algorithms.

For those reasons, there are efforts to keep the LPBF generated workpiece directly on the substrate plate and use it directly for referencing through the whole process chain [4].

In order to ensure the referencing between the LPBF machine and the substrate plate, zero-point clamping systems are offered by machine manufacturers and clamping technology companies for the LPBF process (see Figure 1, right) [5]. However, the substrate plate wears out due to the separation of the LPBF generated workpiece from the substrate plate by sawing or wire electric discharge machining (wire EDM). The substrate plate is a temporary material plate and for each new plate, the reference elements for the zero-point clamping system must be added again. Additionally, there is a lack of automation and high processing costs due to manual or partial manual separation of LPBF workpieces from the substrate plate.
In this paper a new substrate unit system is presented, which allows building the LPBF workpiece on consumable connection elements.

2. Concept development and LPBF analogy substrate unit trials

2.1. Concept of the novel substrate unit

The concept of the developed referencing plate includes consumable connection elements (pins) that can be removed by a simple release mechanism (Figure 2). These pins are designed as simple cylindrical dowel pins with plane end faces (Figure 2, #1).

The LPBF process does not create a bond with the substrate plate, because a heat resistant ceramic protection layer covers the referencing plate. The protection layer is an AlO-coating with a layer thickness of 90 µm. Only the consumable connection elements are bonded to the first built-up material layers of the workpiece. This enables a permanent installation of referencing elements on the referencing plate, because the reference plate is not wearing out anymore.

To generate a workpiece, the following steps have to be considered — similar to a typical LPBF process: First, a powder layer is applied on the referencing plate and a simple basic form is created by the LPBF process. The basic form covers the projected base area of the LPBF workpiece and encloses the connection elements in that area of the referencing plate (Figure 2, #2). In the next step, the workpiece is built up layer by layer on the basic form. After finishing this layer-wise process, the workpiece can be transported through the production process chain on the referencing plate. The accessibility of the workpiece is given for subtractive machining (e.g. milling) and measurements for five sides. The referencing and clamping process of the substrate unit can be achieved automatically via the zero-point clamping system mounted on the bottom side. (Figure 2, #3)

After all operations along the manufacturing process chain such as machining operations have been done, the connecting elements can be released mechanically out of the reference plate (Figure 2, #4). Following, the connection elements can be removed from the workpiece by a cutting process like wire EDM or sawing.

The analogy substrate plate is made of high temperature steel X10CrAl24. The basic design as single plate offers the possibility to test different connection elements at different distances to each other. The matrix pattern of the connecting elements with different distances between the elements were selected at 15 mm, 10 mm and 7.5 mm to check which bridging distances are possible for different workpiece geometries. The cylindrical connection elements have a diameter of 5 mm and a clearance fit of g8-H7 (minimal clearance 4 µm, maximum clearance 34 µm). The connection elements were standard dowel pins and dowel pins with additional conical head to increase its upper end face.

In the experiment, various cubic test workpieces were generated in the LPBF process on one connection element at least. The generated geometric features were printed on the one hand with direct contact to the reference plate and on the other hand with contact only to the connection elements. The contactless geometric features have a bridge-like basic form with a 45° angle between reference plate and workpiece surface, according to LPBF design guidelines [6, 7].

The analogy trials were carried out on a Concept Laser M1 machine, which had a zero-point clamping chuck integrated ex factory. Table 1 summarizes the selected process parameters as well as the boundary conditions of the LPBF process.

Table 1. LPBF process parameters and boundary conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBF machine</td>
<td>Concept Laser M1</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>25 µm</td>
</tr>
<tr>
<td>Hatch scan speed</td>
<td>1250 mm/s</td>
</tr>
<tr>
<td>Contour scan speed</td>
<td>1000 mm/s</td>
</tr>
<tr>
<td>Powder material</td>
<td>Nickel based alloy IN718</td>
</tr>
<tr>
<td>Process heating</td>
<td>off</td>
</tr>
<tr>
<td>Laser on delay</td>
<td>0.212 ms</td>
</tr>
<tr>
<td>Laser off delay</td>
<td>0.533 ms</td>
</tr>
</tbody>
</table>

In order to achieve a precise referencing of the machine mounted laser scanner to the analogy referencing plate, a manual referencing was carried out between both elements. The geometrical position pattern of the whole reference plate was imported in the control software of the LPBF machine so that every connection element can be obtained individually and precisely.

The results of the LPBF tests show that various geometry features could be successfully generated on the connection elements (Figure 3).

2.2. LPBF trials with analogue substrate unit

An analogue substrate plate was produced for further experimental investigations for the following reasons:

- Verification of the basic feasibility (mechanical function, thermal stress)
- Creation of different basic geometry features on the connection elements
- Analysis of different distances of the connecting elements
- Investigation of the separation of connecting elements after the LPBF workpiece generation
Especially the geometry features with bridge-like basic form could be generated with good quality and process stability. The distance between the connecting elements must be minimized, depending on the workpiece size, otherwise excessive residual stresses occur. These stresses can lead to cracks in the workpiece followed by detachment from the connection elements. The geometry features with a bridging distance of 7.5 mm and 10 mm were successfully generated. In contrast to this the 15 mm bridging distance had accidental detachments. The test workpieces with direct contact to the substrate surface unit had only a slightly material bond due to the AlO-coating. This reinforces the initial idea of using a coating to prevent a material connection. The separation of workpieces with surface contact led into damages of the coating. Pulling out the test workpieces with connecting elements worked for all these test workpieces. Also longer cuboids with dimensions of 220x20x20 mm³ could be generated. Due to the residual stresses, the edges of the cuboid were slightly pulled out together with the connecting elements. However, a pull-down mechanism for the connecting elements would prevent this and is intended for the detailed design of the substrate unit.

3. Functional design of the novel substrate unit and validation

The novel substrate unit has 412 holes for the connection elements in a matrix pattern with a grid spacing of 10 mm. The clamping of all connection elements is realized simultaneously using a clamping plate. This clamping plate is located between the upper AlO-coated substrate plate and a lower base plate (Figure 4). The guides of the clamping plate are extended by an adjustable dovetail guide so that clearance-free adjustment can be achieved. Through the linear movement of the clamping plate, the connection elements can be pressed onto the base plate through specially designed slot holes (keyhole shape).

Before starting the LPBF generation validation trials, the substrate plate hole pattern was loaded into the machine and referenced so that the laser could always accurately hit the connection elements. The geometries were successfully generated in the LPBF process, as shown in figure 7.

4. Summary and further work

For many components manufactured with LPBF, clamping and referencing within a subtractive manufacturing process chain is a bottleneck that does not allow economic use. Current substrate plates usually only serve the purpose of generating a LPBF workpiece. The life cycle of the substrate plate is not taken into account.
This paper showed a new developed and validated LPBF substrate unit system, which allows to generate LPBF workpieces on consumable connection elements. This enables to use the substrate unit as a system for referencing and clamping with the advantages of zero-point clamping systems. A standardization of the clamping and referencing process over the entire process chain was create. This will raise the automation degree. Process steps for removing the workpiece can be minimized, which will reduce the secondary processing times.

The further work will concentrate to perform tension and shear test to analyse the connection strength between the connection elements and the LPBF workpiece. The experimental validation of different powder materials as well as the analysis of different bridge structures of the LPBF basic form should be performed.

The new substrate unit enables the integration of cartridge heaters between the connection elements, which will affect the deviation of the LPBF workpiece positively. This will be part of future research activities.

5. Acknowledgement

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References