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ABSTRACT

The combination of the laser powder bed fusion of metals process (PBF-LB/M) with mechanical finishing using state-of-the-art machining centers enables the production of high-performance structural components with both internal and external complexity and precision. However, the sequential machining of additive manufactured parts can be challenging due to the need for multiple clamping setups and part-specific clamping devices. Postprocessing typically accounts for 20%–40% of manufacturing costs and can even double the cost of the final part. To reduce component costs, mechanical postprocessing should be considered. This study presents a novel concept for the development of resource-efficient add-on structures that can simplify mechanical postprocessing. These structures can either be applied to the part design prior to additive manufacturing or integrated into the part's support structures. The developed structures allow the direct mounting of near-net-shape components on automatable, state-of-the-art parallel clamping systems. The structures are designed to clamp the parts with increased accessibility for five-sided simultaneous machining. The additional material costs are calculated within the work. The procedure for generating the add-on structures for additive manufacturing, using bounding box, topology, and shape optimization is presented. The mechanical behavior of the add-on structures is verified by clamping and measurement tests. The developments were validated by the manufacturing of three different components from the aerospace and laser technology sectors, using PBF-LB/M and aluminum alloy AlSi10Mg. The overall functionality of the add-on structures was validated by finishing the functional surfaces of the components and mechanically removing the support structures, using five-axis vertical milling centers.

Key words: Additive manufacturing, L-PBF, post-processing, 5-axis machining, clamping, lightweight design, topology optimization, add-on structures

I. INTRODUCTION

The opportunities arising from additive manufacturing (AM according to ISO/ASTM 52900:2022[1]) have been extensively described.[2,3] AM offers a unique combination of design flexibility and precision that conventional manufacturing processes are unable to achieve.[4] The application of mechanical, thermal, or other optimization procedures enables the design of components that would previously have been impossible to manufacture.[5–7] In metal AM, the laser powder bed fusion process (PBF-LB/M according to ISO/ASTM 52900:2022) is of particular significance, as it is one of the most widely used AM technologies and is increasingly being used to complement traditional methods such as casting or machining.[8,9] In 2023, the industrial market for metal AM experienced a 14.6% growth, with PBF continuing to be the most relevant technology, leading in terms of both maturity and annual sales.[10]

However, PBF-LB is also restricted by process-related limitations.[11–13] Consequently, the manufactured components typically have to be reworked by post-process machining.[14–16] By combining the laser powder bed fusion process with mechanical finishing using state-of-the-art machining centers, the advantages of both additive and subtractive manufacturing can be fully exploited.[17–19] At the same time, there are still significant obstacles to the automation of the sequential machining process.[20] Post-processing represents a particular high proportion of costs, with a typical range of 20%–40%; in some cases, it can even double the cost of the final part.[21,22]

One of the most significant challenges in the field of mechanical finishing is the secondary clamping of complex, usually topologically optimized near-net-shape components.[23,24] The utilization of parallel clamping devices, which are already employed in a highly automated way in five-axis machining centers, is typically not feasible. In most cases, part-specific clamping devices for several component clamping operations must be designed and set up manually.[25] These are associated with particularly high costs and low automation. In addition to the external complexity of near-net-shape components, the automation of component clamping is also made more difficult by the increasing product individualization.

In order to improve clamping for machining, design for additive manufacturing (DfAM) recommendations for adapting the AM part design with respect to finishing have been described.[26] Maucher *et al.* propose a framework of design rules considering additional major topics such as the support structure design or probing (determination of the workpiece coordinate system).[27] Most part-design-specific approaches are aimed at the utilization of parallel clamping devices, which is mainly derived from the field of casting technology.[28] The most significant approach is the parallelization of individual design elements. Waldschmidt *et al.*[29] successfully demonstrated the integration of add-on structures into the support structures of an aircraft bracket with the objective of utilizing parallel clamping. Some approaches that focus on parallel clamping also discuss the consideration of clamping or machining forces within topology optimization. For example, Benoist *et al.*[30] discuss the consideration of functional surfaces within a part-specific topology optimization. Langelaar[31] investigates the consideration of cutting forces and support structures as design space within a part-specific optimization. His objective was to clamp the build platform (build plate). In this case, the support structures must have sufficient stiffness to hold the part on the build plate during machining. Didier *et al.*[32] took a similar approach, focusing on a numerical methodology to determine the cutting forces and considering lattice support structures.

The procedure of clamping the AM build plate for machining differs from the procedure of separating the components from the build plate after AM and, subsequently, clamping them via add-on structures or fixtures. The main advantage of build-plate-clamping is the potential elimination of the need for additional add-on structures or fixtures for the first clamping setup. It is also possible to transfer a position reference established for AM to the machining center via AM zero-point clamping systems. The most significant drawback of clamping the build plate is the restricted accessibility during machining when multiple components are to be manufactured in a single build job. This is contrary to the approach of a potential series production or an increase in productivity by placing the components as close together as possible to improve the utilization of the available build space. Modified segmented build plates can mitigate this disadvantage and are particularly suited to service providers that specialize in both additive manufacturing and machining. Another disadvantage of build-plate-clamping is the necessity to transport or ship AM build platforms, which is of particular relevance when different service providers work together.

In contrast to part-specific design approaches, this passage presents approaches that focus on the development of add-on structures that can be applied to different part design cases (AM geometries). A promising approach to the design integration of the so-called CNC-RP fixtures was presented by Boonsuk and Frank[33] and Manogharan *et al.*[34] The principal limitation of the concept in terms of its applicability is the necessity for a four-axis milling system with a specific trunnion table kinematic. In addition, a large amount of additional materials is required for both the add-on and additionally required support structures. However, if the required machine kinematics are available, the method is characterized by high accessibility during the CNC milling process. Generally, if the accessibility of cutting tools to multiple surfaces that require machining can be improved within a single clamping setup, further clamping setups may be avoided, which leads to a potential reduction of time and costs during finishing. Another promising approach for AM-integrated add-on structures was presented by Ferchow *et al.*[35] This approach also promises a high level of accessibility within a single clamping setup. In order to facilitate sequential mounting on a specific three-jaw chuck manufactured by GRESSEL-AG, the so-called AM-integrated bolts are added to the AM design. However, this introduces a significant limitation, as this specific clamping system is not widely used in the field of CNC machine tool technology. Compact parallel clamping vices have a wider range of applications and improved automation potential, thanks to their smaller installation space as well as broader connection interfaces in the area of zero-point clamping systems [cf. Fig. 1(b)].

The same applies to the add-on structures and support structures used as a part of the clamping structure within a single setup: these usually need to be removed from the part in a subsequent operation, which can lead to increased costs. In some cases, a subsequent setup is required to gain access to other areas of the part, which can also be used to remove the add-on structures or support structures.

This work presents the development and testing of novel add-on structures that can be applied to different AM geometries, as shown in Fig. 1. The presented add-on structures are designed to exploit distinct advantages and offer the following novelties with respect to the existing approaches:

- The utilization of compact, widely used parallel clamping devices to complex near-net-shape AM parts, additionally offering high accessibility for five-sided machining.
- The add-on structures can be form-fitted into the parallel clamping system, thanks to the interface design, reducing clamping forces, and, thus, material costs.
- The clamping interface features locating holes for probing the component center point in the x–y plane (cf. Fig. 3).

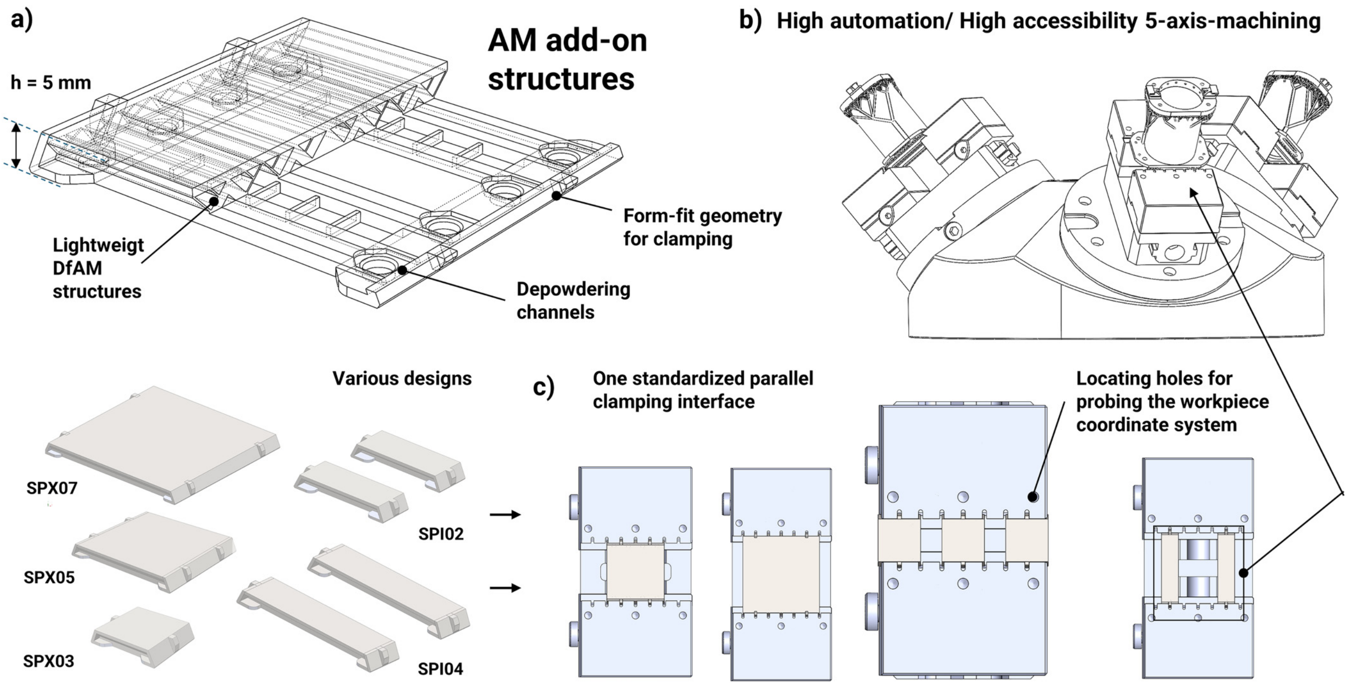

FIG. 1. (a) Add-on structure design. (b) High automation AM demonstrator setup. (c) Form-fit parallel clamping interface.

- The add-on structures can be integrated either within the AM component design or within the component's support structures.
- The add-on structures are designed with regard to DfAM and a resource-efficient lightweight construction as well as topologically optimized based on reduced clamping forces.

II. MATERIALS AND METHODS

Sections II A and II B present the procedure for creating the add-on structures. The static analysis of the created structure types and the validation of the overall system with respect to its usability for various industrial use cases is presented in Sec. III.

A. Add-on structure design procedure

This section presents a procedure for generating add-on structures based on the specific AM design use case. The developed procedure can essentially be described by four steps, which are referred to here as (1) design space to part, (2) 2D DfAM structure, (3) topology optimization, and (4) volumetric modeling, which is shown in Fig. 2.

(1) *Design space to part*: The design space is dimensionally defined with regard to the part-specific available integration space or the existing connection area for the assembly with the component or the support structures for AM. The height of the box is defined by the design interface of the clamping system. In this study, a design interface with a height of 5 mm was developed for the form-fit mounting of various types of add-on structures, as shown in Fig. 1(a).

(2) *2D DfAM structure*: Based on the preferred AM orientation and the established DfAM guidelines, a standardized two-dimensional internal structure pattern [cf. Fig. 2(2)] is applied on the plane orthogonal to the clamping force direction. This internal structure is then extruded in three dimensions, using the design space as defined in (1). The box is then assembled with the developed clamping structure, which serves as a standardized form-fit interface to the clamping system, as shown in Fig. 3.

(3) *Topology optimization*: The generated part from (2) is topologically optimized according to the load/bearing constellation in the clamping system. The objective is to reduce the volume of the material used. Additional to the internal DfAM structure, boundary layers of at least 1 mm with contact to the clamping system, component, or support structure are defined as the nondesign space. The resulting design iterations are prioritized with respect to DfAM.

(4) *Volumetric modeling*: This step is optional if CAM planning tools are employed that work entirely with tessellated geometry information. In this case, the channels for powder removal can also be incorporated as nondesign space within the topology optimization process (3). However, in order to fully incorporate the add-on structures into virtual CAM planning, parametric geometry information [in contrast to the triangular design iterations from (3)] is usually required. Consequently,

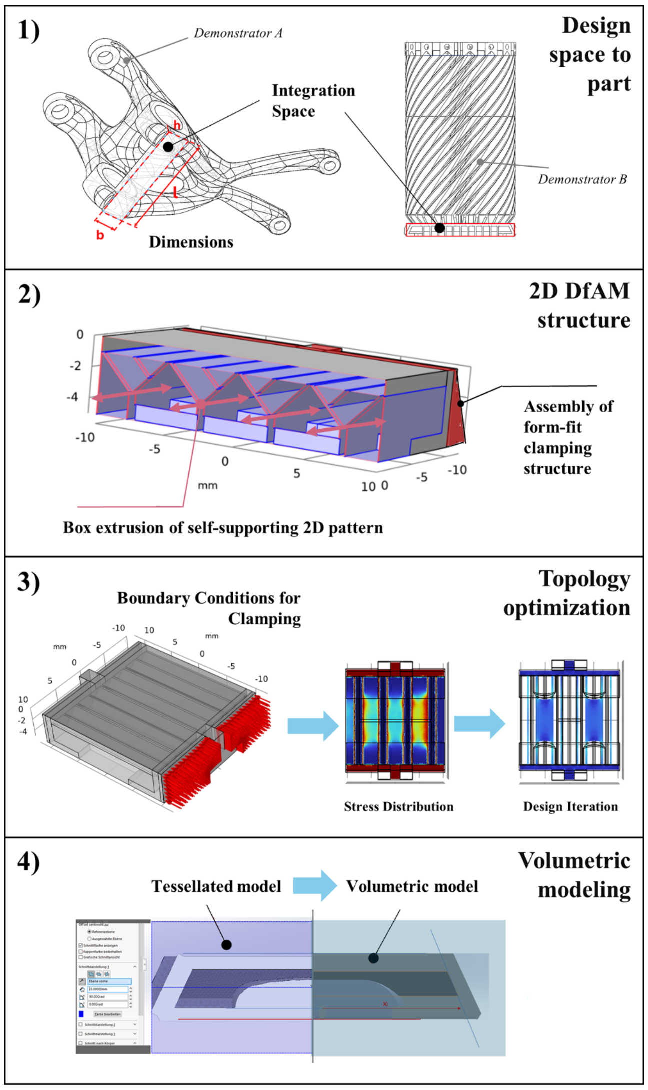

FIG. 2. Add-on structure design procedures (1)–(4).

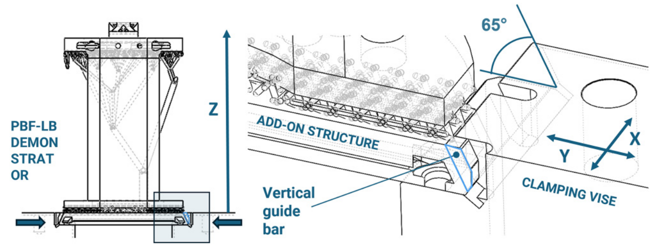

FIG. 3. Add-on structure clamping interface design.

the final step is the execution of a CAD-based shape optimization. The parametrically modeled box with the geometry from (2) is revised on the basis of the design iterations from (3). Unnecessary volumes are removed, transitions and radii are optimized, and channels are added to allow the sequential removal of the internal powder material.

In this study, ten distinct add-on structure types were developed following the previously described procedure. Five of these are presented in detail in this paper (cf. Fig. 7) and were experimentally analyzed within this study. The greater the number of add-on structure types, the more likely existing add-on structures can be applied to new AM design cases and the broader the range of AM geometries that can be utilized.

B. Materials

The internal 2D structure pattern [cf. Fig. 2(3)] was designed based on a simple repeating self-supporting branch structure with angles of 45°. A minimum wall thickness of 0.6 mm was used for the branches. As contact part to the clamping interface, the same clamping structure geometry was used for each add-on structure type, incorporating a 65° bevel and vertical guide bars as shown in Fig. 3. This form-fit interface allows for the complete blocking of all rotational and translational degrees of freedom. Consequently, the necessary clamping forces can be reduced in favor of a resource-efficient design optimization as shown in Fig. 2, step (2). The developed clamping interface enables the form-fit mounting of the add-on structures to an AVANTI contour clamping system[36] from LANG Technik GmbH. This is a compact parallel clamping system that incorporates a quick-change jaw mechanism. The jaws are simple to fabricate and can be modified to accommodate various component applications. Based on this system, two standardized clamping structures and complementary clamping jaws were developed as part of the research project. Because of the better results obtained, the focus was placed on a single variant, as illustrated in Fig. 3. The jaws have locating holes for probing the center of the workpiece coordinate system in the plane (x- and y-coordinates). The probing of the z-coordinate is done on the clamped part. As an alternative to a centrally clamped part, multiple parts can be clamped at different positions, as shown in Fig. 1(b).

The objective of the topology optimization in (3) is the optimal distribution of materials in a given space (design space) by minimization of the mean compliance C. The design space was discretized using rectangular elements (hexahedrons). The solid isotropic material with penalization (SIMP) approach with a Helmholtz filter as implemented in COMSOL Multiphysics 6.0[37] based on Bendsøe and Kikuchi[38] and Bendsøe and Sigmund[39] was used in this work. Within the optimization, design proposals were generated for various volume fraction restrictions ($V_{frac} = 0.1–0.9$), which were then analyzed with regard to the global displacement maxima. In addition, the design proposals were also analyzed in terms of lattice homogeneity and suitability for additive manufacturing. The work was implemented in COMSOL Multiphysics version 6.0. AlSi10Mg was implemented as a material for all mechanical structures. Figure 4 shows the analysis of the displacement maxima of various design proposals using the design concept for the add-on structure SP03X, which were generated under varying volume fraction restrictions.

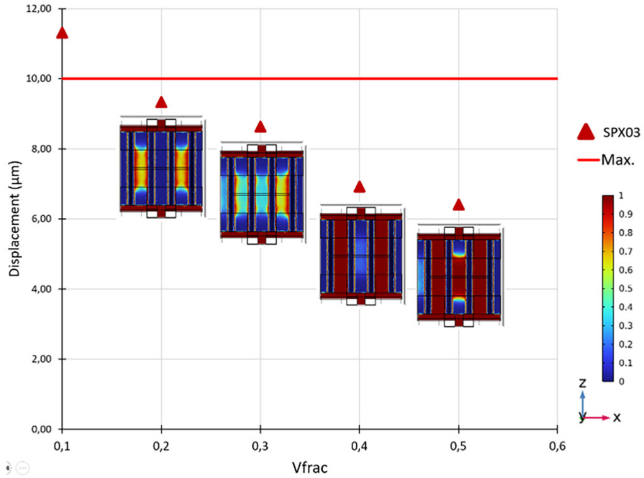

FIG. 4. Displacement based on volume fraction (SPX03).

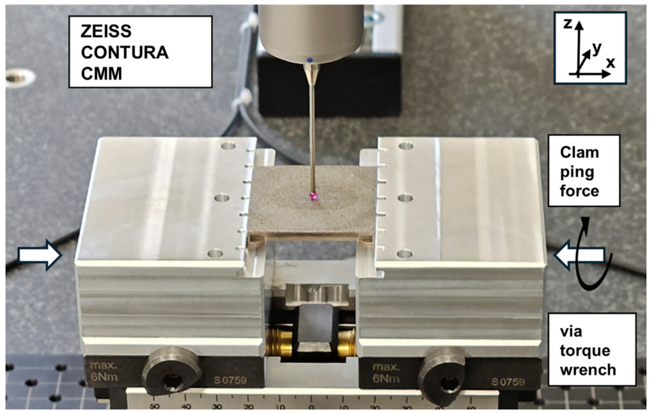

FIG. 5. Setup for the clamping experiment.

The volumetric modeling as shown in Fig. 2(4) was implemented in SOLIDWORKS 2023.[40] The powder removal channels were provided with 3 mm diameter holes.

III. RESULTS

A. Clamping experiment

1. Materials and measurements

This section presents the methodology and test setup used to examine the additive manufactured add-on structure samples using clamping tests. This section is also used to present the developed add-on structure types in more detail. Figure 5 shows the clamping test setup using the example of the add-on structure type SPX05 ($40 \times 40 \times 5\ mm^3$).

The add-on structure test samples were fabricated on a 2021 OCM MPrint + PBF-LB/M system using AlSi10Mg. The different samples were manufactured with a layer thickness of 20 μm each. After additive manufacturing, the samples were separated from the build platform by wire EDM and placed on the target clamping interface, which was permanently mounted on a ZEISS CONTURA 9/12/8 bridge-type coordinate measuring system. The specimen-specific clamping forces were applied incrementally using an adjustable torque wrench that was calibrated prior to each application using a GEODORE DREHMOTEST E torque tester. After each clamping force application, the tactile measurement cycle was performed.

Five different types of specimens (add-on structure types) have been tested. Within each specimen, the response functions of 7/8 measuring points (SPX/SPI versions) were measured for various load cases, as shown in Fig. 7. The positioning of the jaws in the direction of the specimen was measured by the position of two reference bore holes on the jaws in the x-coordinate (cf. Fig. 5). The aim of the investigation was to determine the extent to which the specimens deform symmetrically in the jaw direction with increasing clamping force. In addition, 5/6 points (depending on SPX/SPI versions) were measured on the specimen surface in the z-direction to determine the displacement of the surface that represents the attachment area (contact area) to the component or the component's support structures. The measurement results are shown in Fig. 7.

In case of the jaw displacement (x-direction position), the displacement values were centered on the mean value of CL + Y and CL − Y. The sample surface displacement values (z-direction position) were centered on the center value of the sample surface (X0/Y0 for SPX versions or X0/−Y/ X0/+Y for SPI versions). The centered values are used as reference values. In order to provide a deeper context for the z-direction contact surface measurements, additional topography profiles were measured for each measurement cycle, as shown in Fig. 6 for SPX05 at 2500 N.

In Fig. 7, the tested add-on structure types are also shown with respect to their key performance characteristics. In addition to the basic dimensions, the contact area represents the

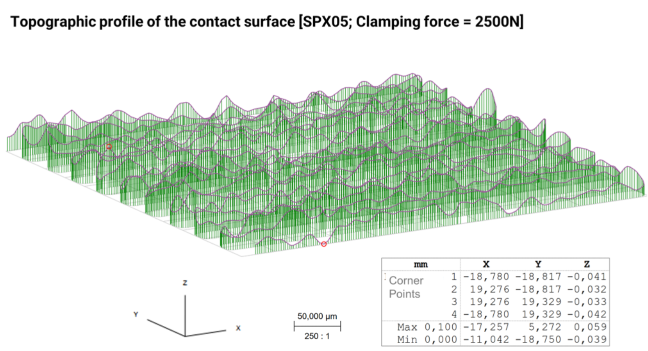

FIG. 6. Topographic profile of the contact surface (SPX05).

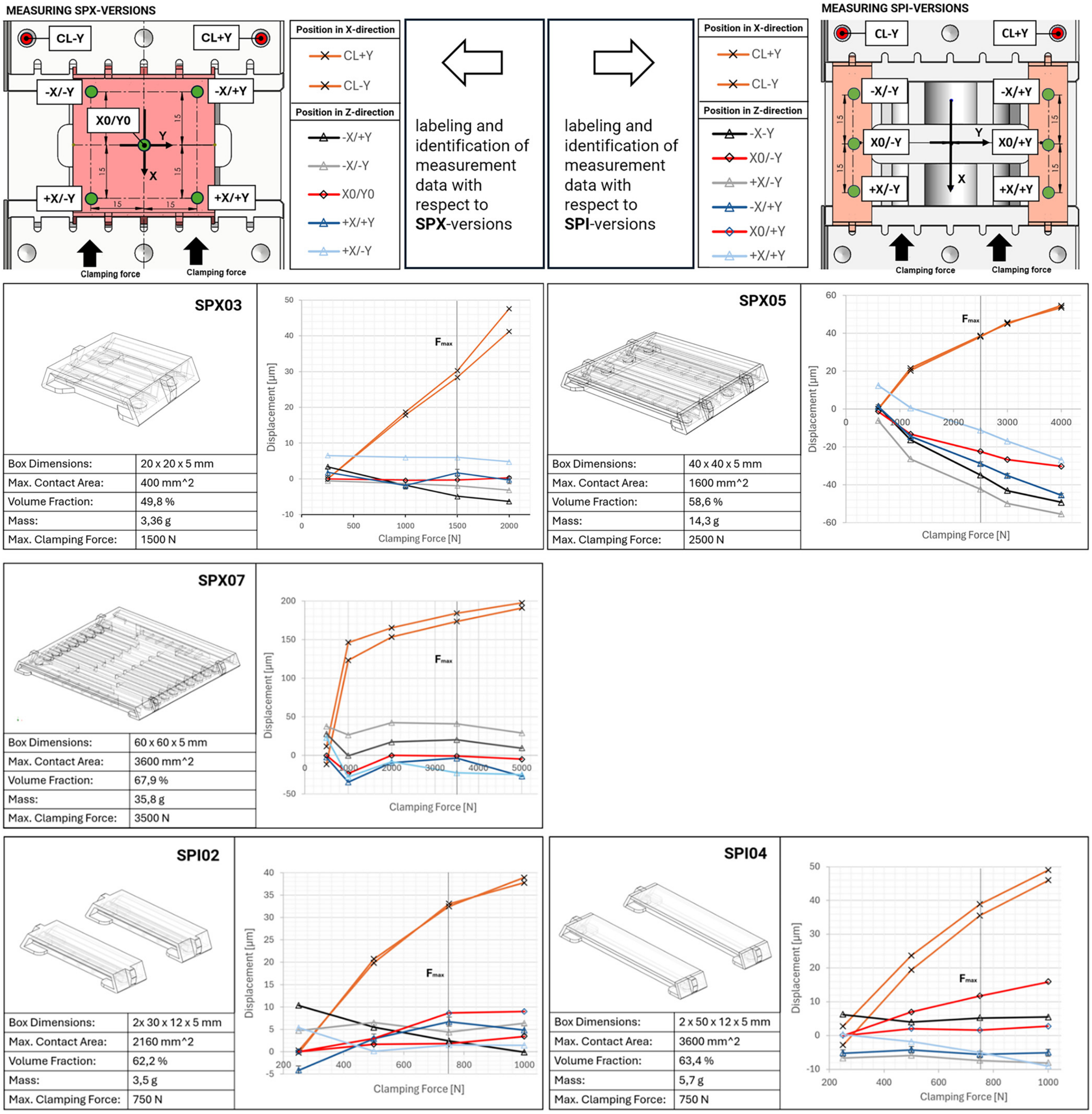

FIG. 7. Clamping experiment testing results for various add-on structure types (SPX/SPI versions) made from AlSi10Mg.

area that can potentially be connected to the existing AM design. The SPI versions can be mounted at different distances from each other on the clamping interface, allowing the contact area to be varied depending on the application. The calculated material overhead is represented by the component mass. With regard to the aspect of lightweight construction, the volume fraction indicates the proportion of the displayed box dimensions that are volume related.

2. Interpretation of test results

This section analyzes the displacement values of the specimens in Fig. 7. The analysis of the orange-colored graphs of jaw displacement (CL − Y; CL + Y) in the direction of the specimen reveals a consistent trend: With increasing clamping force, there is a corresponding increase in jaw movement in the direction of the specimens (x-direction). Based on this information, it is then necessary to analyze the extent to which the jaw displacement affects the plane alignment of the specimen surface in the clamping system. A nonplanar alignment would have a direct effect on the alignment of the AM components connected in this area when using the add-on structures. The alignment of the sample surface is represented by 5/6 measuring points (SPX/SPI versions) on the sample surface (position in z-direction). A certain relative deviation of the surface measuring point Δz can be determined for all samples even at lower clamping forces. Topography profiles were also created for this purpose (cf. Fig. 6). This deviation essentially represents the topographic profile of the additively manufactured samples in the unloaded state, immediately after additive manufacturing and separation by wire EDM.

As the load increases, these differences diminish for some sample types (cf. Fig. 7, SPI02), as the samples are pressed into and align with the form-fit mounting interface. This desired alignment based on the clamping interface can also be observed in cases where the relative height difference of the measuring points (planar alignment) does not change, but the overall z-height of the sample surface does (cf. Fig. 7, SPX05, SPX07). In contrast to the x-/y-coordinate referencing, the z-coordinate position of a connected AM part is not referenced to the clamping system, but to the part. A possible slight difference in height of the add-on structure in z with parallel alignment of the mounting surface is, therefore, irrelevant during use. However, a desired alignment with the clamping geometry can also have a negative effect (stronger Δz-deviation, less planar alignment) in this experiment, in that a deviation in the sample surface, which is already present as a result of additive manufacturing, only becomes visible as a result of the alignment. F_{max} represents the load limit that was considered as a boundary condition in the topological optimization of the add-on structure types. As expected, the largest Δz deviations in diagrams develop, as the load limits are exceeded.

The Δx values represent the alignment of the jaws in the sample direction. These remain largely stable as the load increases, only diverging when the load limit F_{max} (SPX03, SPI02) is exceeded. This shows that the jaws adjust symmetrically in the specimen direction.

It is important to note that the clamping forces applied in this experiment significantly exceed the clamping forces required for precision finishing of near-net-shape components. Rough machining is typically not required for near-net-shape components. The maximum machining forces that occur during precision finishing are typically only in the range of 200–300 N.[41,42]

B. Validation by use cases

In this section, the testing of the add-on structures is presented through their application to three different industrial use cases. The components that were equipped with different add-on structures for the investigation are shown in Fig. 8.

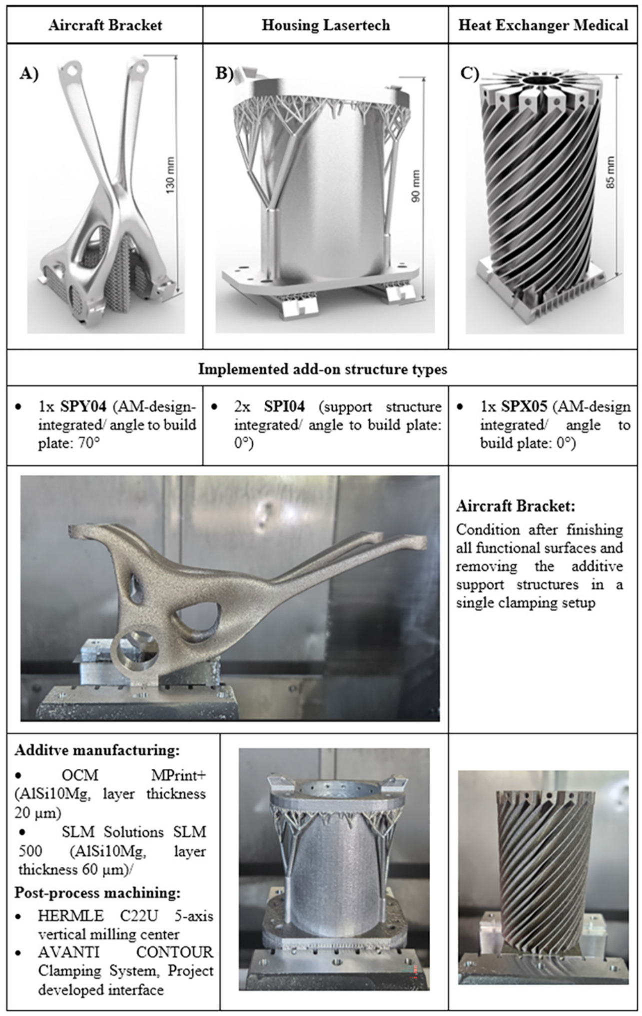

FIG. 8. Use case scenarios for add-on structure application.

The aircraft bracket shown [cf. Fig. 8(a)] was already equipped with add-on structures in a previous study by Waldschmidt *et al.*[29] in order to be able to clamp the part within two clamping setups with a parallel clamping system. In this study, a much more effective solution was achieved, providing the following advantages:

- Optimized orientation for additive manufacturing [cf. Fig. 8(a)].
- Complete finishing of all functional surfaces as well as removal of additive support structures within a single clamping setup.
- Particularly low additional cost by adding the SPY04 add-on structure (∼3% of total part mass).

The add-on structure SPY04 is a further developed variant of the structure type SPI04, which can only be integrated in the AM component design. The aircraft bracket was clamped with a force of 500 N and could be fully machined without any significant problems. As another industrial application, the Lasertech actively cooled housing [see Fig. 8(b)] was equipped with two SPI04 add-on structures that were integrated into the part's support structures. This thin-walled component serves as housing for a laser system and contains a complex internal cooling channel geometry that can only be provided by additive manufacturing. Lattice structures were used as support structures between the component and the add-on structures. All use case scenario parts were machined on a HERMLE C22U vertical milling center in a five-axis milling process. All components were manufactured in two PBF-LB/M variants. In addition to a variant with a layer thickness of 20 μm that was manufactured on a OCM MPrint + system, for each use case scenario, a rougher 60 μm variant was produced, using a SLM 500 system from Nikon SLM Solutions AG. The locating holes on the clamping interface were used to refer the workpiece coordinate systems in the x- and y-coordinates. The z-positions were measured on the clamped component surfaces. As a third component, the heat exchanger from the medical sector [see Fig. 8(c)] was employed as a self-supporting application design. It was directly attached to an SPX05 add-on structure type. Both versions of this part (20 /60 μm layer thickness) could be clamped directly after wire EDM using the developed clamping interface and were machined without any problems. The only component variant that could not be machined was the aircraft bracket, which was manufactured with a layer thickness of 60 μm. In this case, the attached structure type SPY04 was manufactured at an orientation of 70° to the build platform, in which case, the contained vertical guide bars (cf. Fig. 3) had to be manufactured at a critical angle for a support structure-free design of the structures. This was not a problem for the 20 μm version of the part but resulted in a deviant bar geometry for the 60 μm version, which could not be inserted into the form-fit clamping interface.

IV. CONCLUSION AND OUTLOOK

In this study, a new approach for the generation of AM add-on structures was presented and tested. Different add-on structure variants were generated, additively manufactured, and tested for their functionality, in combination with a form-fit mounting interface presented for the first time. For this purpose, the deformations of the additively manufactured samples were measured under the influence of increasing clamping forces. The functionality was further tested by applying it to various components from the aerospace, medical, and laser technology sectors, as well as their additive manufacturing and complete finishing using a five-axis vertical milling center. Based on the research, the following conclusions can be drawn:

- The proposed add-on structure designs can be applied to a variety of AM component designs.
- The presented methodology enables the generation of further application-specific designed add-on structures.
- The add-on structures, in conjunction with the developed clamping interface, enable precise alignment of the near-net-shape components by widely used parallel clamping systems that are already highly automated.
- The presented design of the form-fit clamping interface has proven to be particularly functional and helps to further reduce clamping forces.
- The add-on structures allow parts to be clamped with particularly high accessibility for five-sided part machining, eliminating additional clamping operations.
- The proposed add-on structure designs have proven to be robust against clamping forces as well as precision finishing machining forces that were applied to the use case scenarios.

Looking to the future, there is still great potential for the development of new add-on structure types in terms of the lightweighting aspect they contain. The add-on structure types presented proved to be robust even when subjected to significantly higher clamping forces than those that are typically required for precision finishing. This means that the next generation can be designed to be even lighter, which can further reduce the additional cost of using them in additive manufacturing while maintaining the significant savings in postprocessing. The form-fit clamping interface helps to ensure that the add-on structures are held securely in place when machining forces are applied. In the future, it will also be necessary to investigate the limits of the component machining forces at which possible displacement can be expected.

The add-on structures presented have been designed exclusively for use with the aluminum alloy AlSi10Mg. Another task will be to design and test new types of add-on structures for other materials, such as titanium, which are more prone to warping due to residual stresses. The functionality of the overall system for such materials needs to be investigated. In addition, a more detailed cost analysis should be carried out, considering the removal of add-on structures for different part design cases and how this affects the overall production time and cost. In the future, the flexibility in application to different AM designs can be further increased by investigating other possible orientations to the AM build platform.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Johannes Waldschmidt: Conceptualization (lead); Data curation (lead); Funding acquisition (equal); Investigation (lead); Methodology (lead); Supervision (lead); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **Marcel Dias da Silva:** Investigation (supporting); Methodology (supporting); Supervision (equal); Validation (supporting); Visualization (supporting). **Sebastian Roth:** Investigation (supporting); Software (supporting); Validation (supporting). **Tim Röver:** Funding acquisition (equal); Investigation (supporting); Methodology (supporting); Supervision (equal); Validation (supporting); Writing – review & editing (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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