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Semi-Automated Design Workflow for Bolt Clamping Interfaces to Post-Process Additive Manufactured Parts

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Abstract

Metal additive manufacturing (AM) enables the production of complex and individualized designs. However, most AM parts require post-processing with subtractive manufacturing processes, which can account for a significant percentage of the total manufacturing cost of an AM part. Positioning and clamping of complex AM parts within post-processing machines often lead to increased prestresses and reduced tool accessibility. One concept to address this problem is the integration of clamping interfaces in the part. But this leads to the new design challenge of optimal and material-saving placement of clamping interfaces on the part. To overcome this challenge new design tools are desired that facilitate this work and automatically generate the design of clamping interfaces.

A recently developed clamping system uses bolts that are directly printed onto parts as clamping interfaces. These printed bolts and the clamping jaws of the system enable a unique spatial positioning and rigid clamping of AM parts for post-processing. This work introduces a design workflow that supports the positioning of bolts using a knowledge-based engineering (KBE) approach. The workflow thus allows the user to easily find a feasible clamping configuration and automatically generates the geometries of the bolt-shaped clamping interfaces. As input, the workflow uses the part geometry and an AM build direction. During the workflow, the user can modify the position of the clamping system relative to the part and find feasible positions for bolts. The bolt geometries are then generated automatically, and the part can be exported. This paper describes the workflow in detail and provides a vision for future developments of the tool and its potential for the AM process chain.

Keywords: Additive manufacturing, Knowledge Based Engineering, Automated Design, Clamping Interfaces

Supplementary Material: Demonstration Video, https://youtu.be/0e3eSHzwFvc

1. Introduction

Additive manufacturing (AM) and particularly laser-based powder bed fusion of metals (PBF-LB/M) allow great design freedom. This enables the production of complex and individualized geometries for applications in aerospace, hydraulic, and medical industries [1], [2]. Topology-optimized lightweight brackets are an aerospace application that can save weight through their optimized structure and transfer loads efficiently [3]–[5]. Such structures contain many free-form surfaces which are difficult to clamp for post-processing using conventional manufacturing processes such as milling. However, most AM parts need to be post-processed to achieve specified surface quality and manufacturing tolerances. Post-processing costs can account for up to 40 % of the total cost of AM parts [6], and clamping often leads to high prestresses and reduced tool accessibility [7]. Therefore, clamping interfaces like parallel surfaces are often integrated into the part design [8], [9]. A part can be clamped on parallel surfaces by using conventional clamping jaws, but this results in limited

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accessibility for tools and a higher build volume of the part. Another approach is the installation of zero-point clamping systems in AM machines to clamp the build plate [10]. The same system can be installed in post-processing machines to clamp the build plate and machine the part. A disadvantage of zero-point clamping systems is the limited tool accessibility of poor-quality downskin surfaces facing toward the build plate.

The bolt clamping system (BCS), invented by Schlüssel et al, offers a promising alternative [11]. Integrated bolt clamping interfaces (short: bolts) are added to a part in the design phase and fabricated with the part using PBF-LB/M. The ends of the integrated bolts are clamped on the clamping lines between the clamping jaws of the BCS. The part can be post-processed from five sides with tool accessibility for downskin surfaces and support structures (Figure 1). The applicability of the BCS for AM parts was investigated in a previous study, where a high surface quality was achieved [7]. The BCS can be used to improve and automate post-processing. However, the manual design process of bolts on free-form surfaces is time-consuming, and the identification of suitable bolt locations is challenging as manufacturing restrictions must be considered.

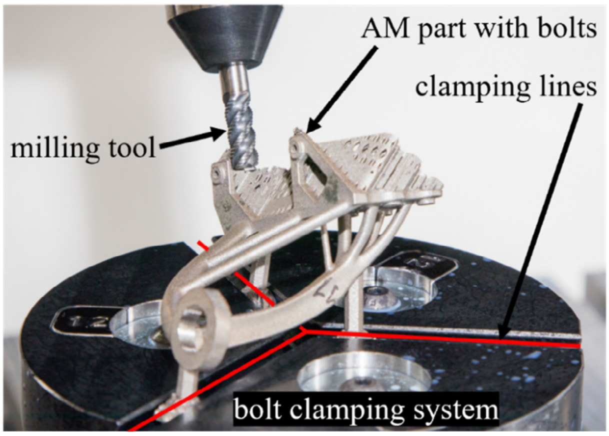

Figure 1 An AM part clamped and milled in the bolt clamping system [7].

The consideration of manufacturing restrictions and characteristics in the design phase is generally referred to as Design for X (DfX), where X is a placeholder for any manufacturing technology [12]. Consequently, Design for AM (DfAM) refers to the consideration of design restrictions like critical overhang angles, minimum wall thicknesses, or critical diameters that cannot be produced without support structures with PBF-LB/M [13], [14]. However, since most PBF-LB/M parts must be post-processed, the consideration of AM restrictions is not sufficient and subsequent steps in the process chain such as post-processing, assembly, or packaging must also be considered during the design process [15]. Wiberg et al. identified four aspects in the DfAM domain [16]: a) component selection and ideation; b) component design and optimization; c) AM preparation and verification; and d) Post-process and verification. In this work, the latter aspect of considering post-processing during the design process is addressed with a focus on bolts and the BCS.

Software-based design tools can be used to support design engineers in time-consuming and challenging tasks [17]. One approach is knowledge-based engineering (KBE), where expert knowledge can be incorporated into design rules [18]–[20]. KBE approaches have been applied to automatically design adaptive fluid channels that consider the critical overhang angle for PBF-LB processes [21]. Furthermore, KBE is used to identify regions that need to be supported and evaluate the tool's reachability for milling processes based on the information of geometrical information of a CAD part [22]. Also, compliance with AM design restrictions within a part design can be evaluated with KBE approaches [23].

The contribution of this work is a new semi-automated design workflow that uses KBE approaches to assist engineers in identifying feasible bolt locations and automatically designing bolts on AM parts. The design of the AM part itself is not within the scope of this work. Throughout the study, the bracket by Klahn et al. [5] is used as a demonstrator and different clamping configurations are compared in a case study. Furthermore, a detailed description of possible extensions is presented for future work to achieve a holistic consideration of post-processing for AM parts in the design phase.

2. Workflow

Figure 2 gives an overview of the five steps of the digital design workflow which are adapted from a simplified process chain that includes design, additive manufacturing, and post-processing. Consequently, it starts with importing a part geometry, which is already designed according to DfAM principles [8] and therefore oriented in the correct build

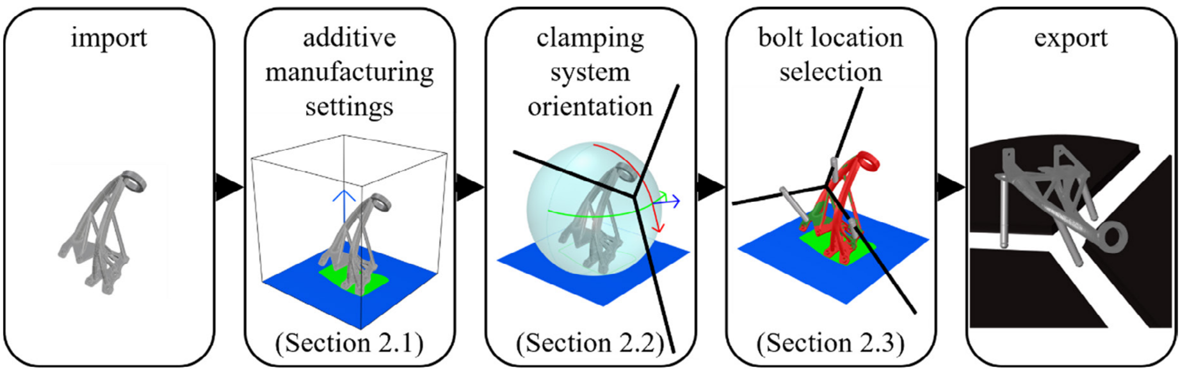

Figure 2 Overview of the individual steps of the digital workflow for creating the bolt clamping interfaces.

direction. Then the AM process is specified (see Section 2.1), and the clamping system is oriented with respect to the part to define the orientation of the clamped part during milling (see Section 2.2). The tool shows possible positions for the placement of bolts on the component to the user. Multiple positions can then be selected and bolts are automatically generated by the tool (see Section 2.3). Finally, a STEP file for postprocessing and an STL file for the AM process is exported as the output of the workflow.

The workflow is implemented in the *Rhinoceros* ® CAD system and its visual programming interface *Grasshopper* ®. The following extension plugins for *Grasshopper* are used within the workflow: Human UI, Metahopper, Human, and Pufferfish.

2.1. AM settings

In the AM settings, the build space is defined by selecting a rectangular or round cross-section and its dimensions. The part, which was previously imported as a STEP file, is placed in the center of the build plate (Figure 3). It is evaluated whether the defined build space is large enough for the part and the part geometry is projected onto the build plate with a convex hull to visualize how much space the part takes on the build plate. The user can control whether the component is oriented as desired relative to the build direction. Furthermore, the critical overhang angle for the selected AM process and material is specified, which is used to evaluate feasible bolt locations.

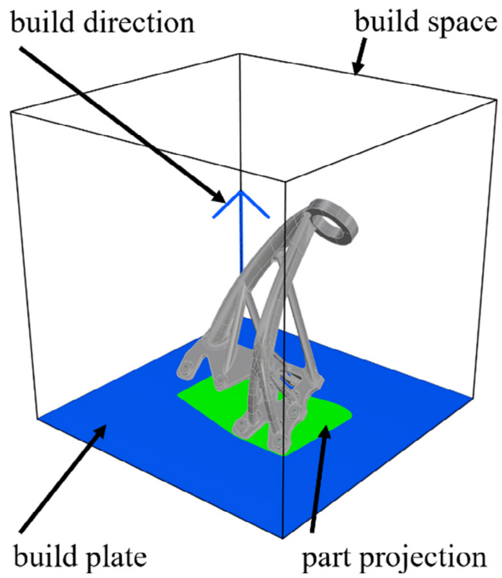

Figure 3 Imported part geometry within build space and with part projection on the build plate.

2.2. Clamping system orientation

A BCS with either three or four clamping jaws can be selected. The BCS is abstracted in the form of clamping lines, which symbolize the space between two adjacent clamping jaws on which the bolts are clamped in the clamping system. Within this work, the version with three clamping jaws is used, which is why three clamping lines are shown in all figures. For the orientation of the BCS, the component is fixed in its position and a clamping plane can be rotated around the part by the three parameters *theta*, *phi*, and *radius* (Figure 4). The clamping plane defines the orientation of the clamping system relative to the part. The exact position of the clamping lines on the clamping plane can be modified through three additional parameters *shift theta*, *shift phi*, and *gamma*. Feasible bolt locations can already be visualized through a colormesh (see Section 2.3) that allows the user to identify feasible bolt locations for a given orientation of the BCS. If the user is satisfied, the process can be continued with the selection of a feasible bolt location. Otherwise, the position and orientation of the BCS can be iteratively optimized using the colormesh for validation.

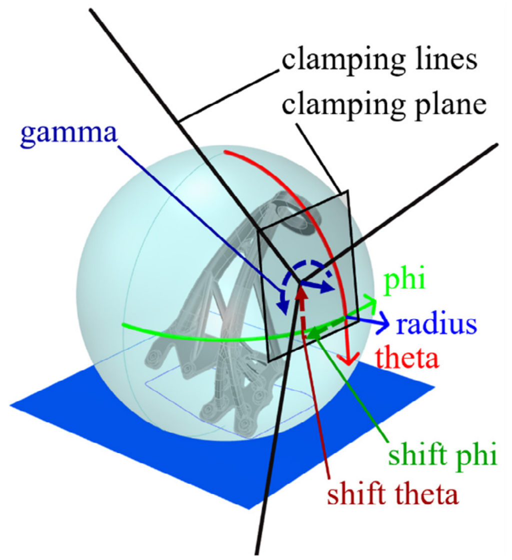

Figure 4 Orientation of the clamping lines around the AM part using the parameters theta, phi, radius, shift theta, shift phi, and gamma.

2.3. Selection of feasible bolt locations

Feasible positions for bolts on the part are displayed using a colormesh with three different colors: Purple areas on the part indicate that they collide with the clamping system and the clamping system position is not feasible. Red areas are not suitable for bolt placement due to design restrictions. Green areas mark areas where bolts can be placed. Figure 5 shows a colormesh and the generated bolts that are created in a later step.

The colormesh is created for a specific position of the clamping system relative to the part. Every time this position is changed, a new colormesh is calculated. The calculation of the colormesh includes a separate consideration of each mesh face and the determination of whether this face is displayed in green, red, or purple. Figure 6 shows the process for determining the feasibility of one mesh face in 3 steps. The first step involves converting the Brep part model into a fine mesh geometry and selecting a mesh face. The clamping lines are further discretized through equidistant sampling points, which serve as possible endpoints of the bolts.

In the second step, the design rules I)-IV) are applied to assess the feasibility of a face as a bolt location on the part. Some of

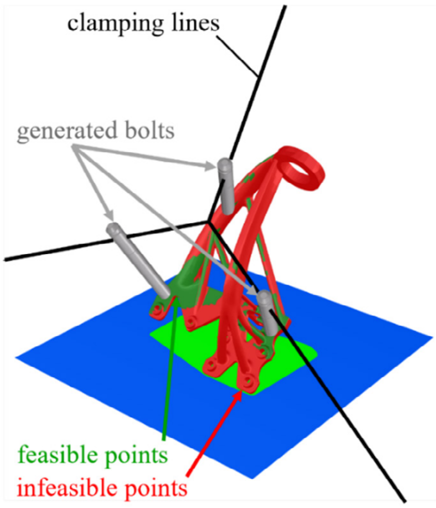

Figure 5 Colour mesh to identify feasible points and generated bolts.

these rules are defined between a sampling point and a mesh face. To conduct the assessment for a specific mesh face, these rules must therefore be applied to all sampling points iteratively. For the assessment of a mesh face with one sampling point, the following design rules are applied in sequence:

rule I. **Collision rule**
The angle α between the normal vector of the clamping system $\mathbf{n_{CP}}$ and the connecting vector of the mesh face to the considered sampling point $\mathbf{v_{FS}}$ is calculated (Figure 6). This angle α must be smaller than 90°, otherwise, the clamping system will be inside the part and cause a collision. In this case, not only is the mesh face unsuitable for a bolt, but the entire clamping configuration is physically not possible.

rule II. **Non-tangent rule**
Calculation of the angle β between the face normal $\mathbf{n_F}$ and $\mathbf{v_{FS}}$ (Figure 6). Angle β must be less than 45° to ensure a good connection between the bolt and the part. If beta becomes larger, this would lead to an increasingly tangential connection of the bolt to the part geometry, which is undesirable.

rule III. **Build angle rule**
The angle γ between the build direction (**BD**) and $\mathbf{v_{FS}}$ (Figure 6) is calculated for the third rule. Angle γ must comply with the AM design restriction of minimal build angle to ensure a fabrication without support structures. The critical build angle is defined in the AM settings (see Section 2.1).

rule IV. **Intersection rule**
For the last rule, it is evaluated whether the connection vector $\mathbf{v_{FS}}$ intersects with the part geometry (Figure 6). Such intersections are not desired, since only faces with a direct bolt connection to the BCS are to be displayed.

In the third step, the color of the mesh is evaluated. If all rules are followed for any mesh area with at least one sampling point, this area is displayed in green. Otherwise, the area is shown in red and if the first rule is not fulfilled, it is shown in purple. Based on the resulting colormesh, the user can select bolt locations and the bolts are automatically generated between the selected point on the mesh and the closest sampling point that is also feasible (Figure 5). To create the bolt, the vector $\mathbf{v_{FS}}$ is used again and a rotationally symmetric bolt is created.

2.4. Case study

The case study demonstrates that the presented design workflow can be used to create different variants of clamping configurations for one part. For this purpose, the aircraft bracket is chosen, as it has already been machined using the BCS [7]. Three different variants are presented in Figure 7: Variant 1 is a reproduction of the clamping configuration that was used by Ferchow et al., variant 2 has a rather small distance between the clamping system and the part, and in variant 3 the bolts have been selected far apart each other.

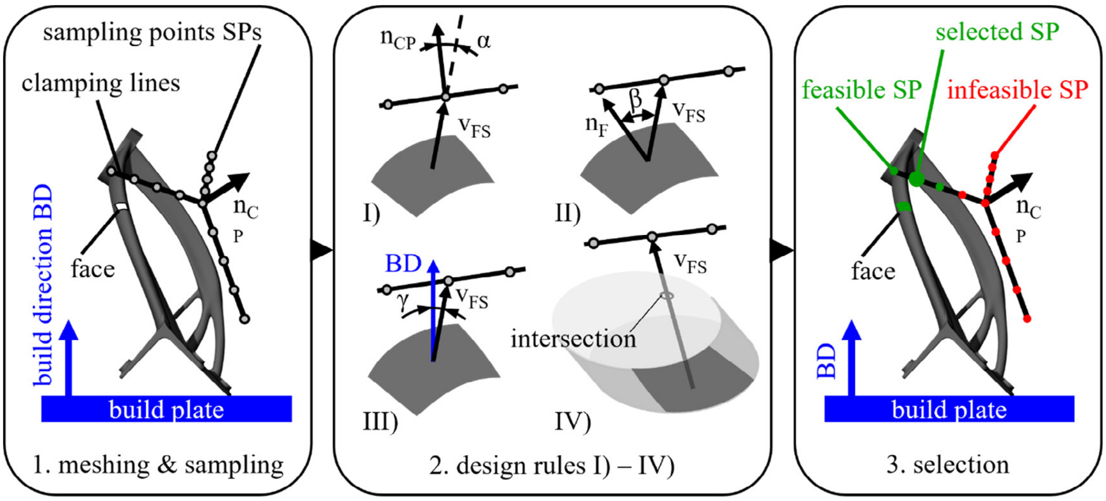

Figure 6 Evaluation rules for assessing the feasibility of a mesh face for bolt placement: A) angle α between $\mathbf{n_{CP}}$ and $\mathbf{v_{FS}}$, B) angle β between $\mathbf{n_F}$ and $\mathbf{v_{FS}}$, C) angle γ between **BD** and $\mathbf{v_{FS}}$, and D) detection of intersections between $\mathbf{v_{FS}}$ and the part geometry.

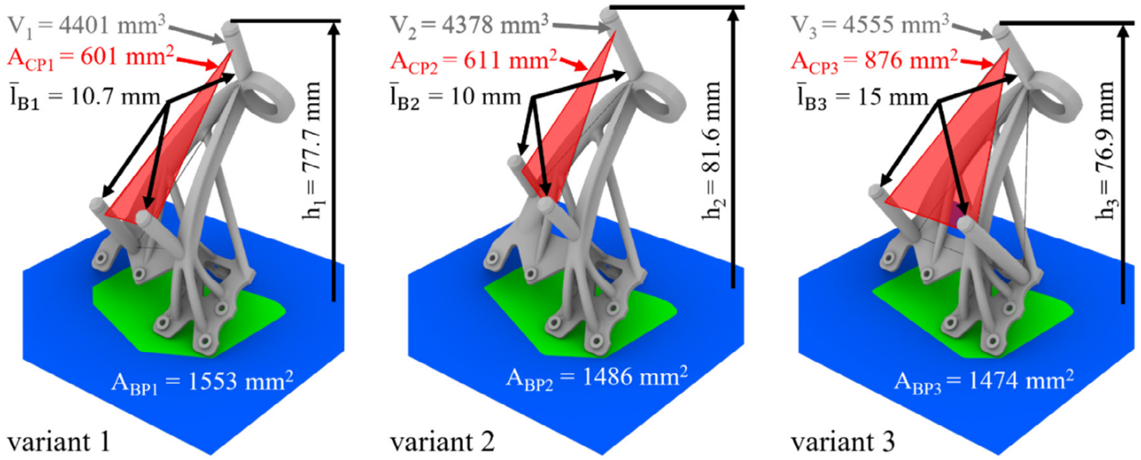

Figure 7 Three generated design variants with clamping surface A_{CP}, build height h, material volume V, mean bolt length $\bar{l}_B$, and projected surface area A_{BP}.

The bolt configuration influences both the AM process costs and the rigidity of the clamping configuration. The AM process costs become higher with an increased projected area on the build plate A_{BP}, build volume V and build height h. The clamping configuration is more rigid with a large area between the bolts A_{CP} and a small mean bolt length $\bar{l}_B$. Different design variants can be compared using these measures and one variant can be chosen dependent on the requirements for a specific part. The comparison of the three clamping configurations shown in Figure 7 illustrates the difficulty of optimizing all parameters simultaneously and that the user often needs to prioritize a specific parameter. In addition, the build height h is increased in all three variants, which is due to the uppermost bolt, which was chosen to support the cylindrical surface during post-processing. This shows how important knowledge of functional surfaces, which need to be post-processed, is for a suitable choice of clamping surfaces. If the cylindrical surface did not have to be post-processed, the uppermost bolt could be selected differently and the build height h would not necessarily increase. For the presented variants, variant 3 would be a suitable configuration as it allows the part to be clamped rigidly and the bolts are placed close to the functional surfaces that need to be post-processed.

4. Discussion and future work

This paper introduced a minimal example of a digital workflow that assists design engineers in placing clamping interfaces for the Bolt-it clamping system on any AM part. By integrating a small user interface [24], the decision about the position of the bolts and the clamping direction remains with the design engineer. The design effort for the application of the BCS is thus strongly reduced and the engineer is supported by visual information on feasible bolt positions. The workflow already excludes infeasible solutions that would violate manufacturing restrictions such as critical overhang angles for PBF-LB. As shown in the case study, different variants can be generated and compared very quickly. This not only reduces the design effort but also improves the choice of stiff and reliable clamping configuration easily.

One advantage of this workflow is its simple logic and modular structure. Therefore, it can be extended with further functionalities or integrated into existing software for AM pre-processing. The vision of a product for such a workflow would then consider all aspects along the AM process chain. In the following, possible extensions are mentioned which bring the workflow closer to this vision and thus provide further research opportunities:

- The inputs can be extended to allow the user to select functional surfaces that need to be milled. Subsequently, a machining allowance can be applied automatically by the workflow to these surfaces. Furthermore, when selecting the bolt placement, it can be ensured that the clamping bolts sufficiently support these functional surfaces and that they are accessible for tools [22].
- When choosing the appropriate bolt locations, the selected metrics in the case study can be used in an optimization algorithm to directly suggest suitable clamping configurations to the user. Such optimization could also consider milling vibrations to further optimize the milling process. Furthermore, the algorithm can be extended to enable the re-use of existing bolts for additional clamping configurations, as shown in Figure 8.

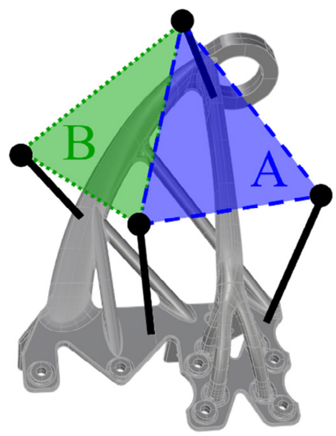

Figure 8 Dual use of two bolts for different clamping configurations A and B.

- The current workflow focuses on post-processing through milling. However, it can be extended with new features for additional post-processing steps or the AM process itself. Potential features for the AM process range from nesting parts on a build plate [25], to automated generation of integrated and sacrificial supports [21], to the identification of violated design restrictions [23]. Other post-processing steps could include automated de-powdering, robotic handling, or automated surface finishing.
- The workflow outputs can be further optimized by integrating software interfaces of computer-aided manufacturing (CAM) tools.

3. Conclusion

This work presents the first version of a semi-automated design workflow, which supports design engineers in the placement of bolt-shaped clamping interfaces on AM parts. The tool directly considers manufacturing restrictions of AM processes and enables the selection of a suitable clamping configuration based on a set of rules. These rules ensure that the bolts can be manufactured together with the AM component and clamped in the bolt clamping system for the postprocessing of AM parts. The work offers an outlook for possible functional extensions to progress towards the vision of considering all steps of the AM process chain during the design process. These functional extensions, such as the automated suggestion of a clamping configuration, the extension to other machining processes and the integration of CAM interfaces, provide further research opportunities.

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