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Research Paper:

Design of a Fixture for Additively Manufactured Workpieces Using Topology Optimization

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Fixing powder bed fusion (PBF) workpieces during post-processing can be challenging owing to their complex geometries and low stiffness. Despite recent reports, fixture planning of PBF workpieces remains a laborious and operator-dependent process. This study proposes an adhesive-based dedicated fixture (ADF) and its design method based on topology optimization. ADF employs adhesives to fix the workpiece and is manufactured by PBF. To verify the effectiveness and reveal potential challenges, a case study using the designed ADF is presented. The proposed ADF offers a fixture planning solution that does not require specialized knowledge and is applicable regardless of the geometry or stiffness of the workpiece.

Keywords: additive manufacturing, powder bed fusion, post-process, fixture design, topology optimization

1. Introduction

Workpieces with low stiffness are important in industries where lightweight and flexible components are essential. During the machining processes of these workpieces, chatter vibration and large workpiece deformation make it challenging to ensure the accuracy of the machined surface [1]. Extensive research has been conducted to understand the underlying physical phenomena and optimize machining conditions and tool paths [2, 3].

Fixturing is another significant factor that influences the quality of machined surfaces of workpieces with low stiffness [4]. Several studies proposed methods for determining the optimal fixture points on a workpiece to improve factors such as positioning accuracy and machining quality [5–7]. Although these studies provide comprehensive theoretical and mathematical frameworks, they focus primarily on fixturing points rather than on entire fixture planning [7]. Other studies adopt a more holistic approach to optimize the overall fixture planning, typically employing either rule-based [8, 9] or statistical approaches utilizing known fixture plans [10, 11]. Rule-based approaches are reliable methods based on experience and physical insights; however, they often have constraints on their applicability, such as requiring specific workpiece features or adhering to a "3-2-1" fixturing principle. Statistical approaches can be highly effective for mass production processes involving typical workpiece features but may not be applicable to unique workpiece geometries that are not included in the existing data. Moreover, neither approach directly evaluates stiffness against cutting forces, which is not ideal for workpieces with low stiffness. In summary, although numerous fixture planning methods have been proposed for specific situations or relatively simple workpiece geometries, methods for optimizing fixture planning for workpieces with low stiffness and complex geometries are lacking.

The lack of fixture planning for such workpieces has become evident with the increased adoption of additive manufacturing (AM), particularly powder bed fusion (PBF). PBF is a popular AM method because of its effectiveness in producing thin-walled and complex geometries with higher resolution than other AM methods [12–14]. The PBF process chain frequently involves post-processing to ensure the quality of printed workpieces, because the printed surfaces are relatively rough and the geometries have printing errors owing to thermal distortions [15]. However, post-processing in AM is generally expensive and requires specialized knowledge [16, 17]. In particular, fixing a PBF workpiece for machining can be challenging and laborious owing to its complexity and low stiffness [18]. Several studies have addressed fixture planning for such workpieces, proposing solutions such as additional sacrificial structures that can be fixed [19] and a matrix-like substrate system that can be used as a fixture [20]. The fixturing system proposed by De Meter et al. [21, 22], which utilizes an adhesive cured and broken by light, allows for easy fixation of workpieces with low stiffness. Although these studies contribute to facilitating fixture planning for PBF workpieces, they remain operator dependent because they lack a clear methodology for placing the fixturing structures. Furthermore, the specialized equipment required in some of these studies hinders their practical implementation.

To overcome the difficulties of fixturing PBF workpieces with low-stiffness and complex geometries, this study introduces an adhesive-based dedicated fixture (ADF) and its design method. An ADF is a dedicated

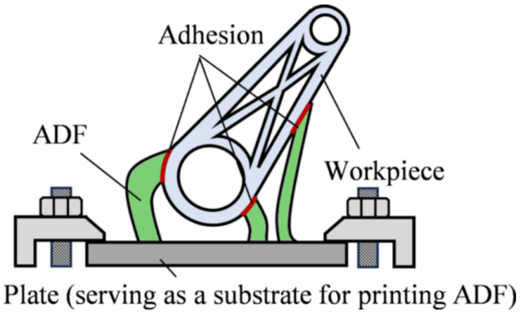


Fig. 1. Schematic of the proposed ADF.

fixture manufactured using PBF for each workpiece, employing adhesives to fix the workpiece while applying a low force. The ADF design method is based on topology optimization (TO) and aims to achieve a non-operator-dependent design process.

This paper first explains the concept of ADF and describes its design method. Second, a case study is presented following each step of the proposed ADF design method. Finally, post-processing of the workpiece using the designed ADF is described, and the challenges of ADF are discussed. It was shown that, despite certain limitations, ADF can be a fixture planning solution without specialized knowledge regardless of workpiece geometry or stiffness. This study contributes to the organization of post-processing PBF workpieces while reducing the dependency on operators.

2. Adhesive-Based Dedicated Fixture (ADF) and Design Method

2.1. Concept of ADF

Figure 1 illustrates the concept of ADF. An ADF is defined as a structure that connects the machine tool and target workpiece and is fixed to the machine tool by capturing the ADF plate. This plate also served as a substrate for PBF printing of ADF. The ADF structure was designed using TO. The clamping force induced by the clampers securing the plate was not directly applied to the main structure of the ADF, indicating that ADF is particularly advantageous for workpieces with low stiffness.

When selecting an adhesive to secure the workpiece, it is crucial to consider its removal process after the machining process. Thermoplastic adhesives that lose their adhesive strength under specific heat conditions are particularly suitable for this application. Similarly, adhesives developed for machining such as light-activated adhesives are preferable. Although residual adhesive may be present on the workpiece after detachment from the ADF, it can be removed during the subsequent blasting process, which is commonly performed in the PBF process chains to improve the surface quality.

The use of ADF instead of conventional fixtures may require additional time for application and cleaning of the adhesives. Therefore, the practical benefit of the ADF is

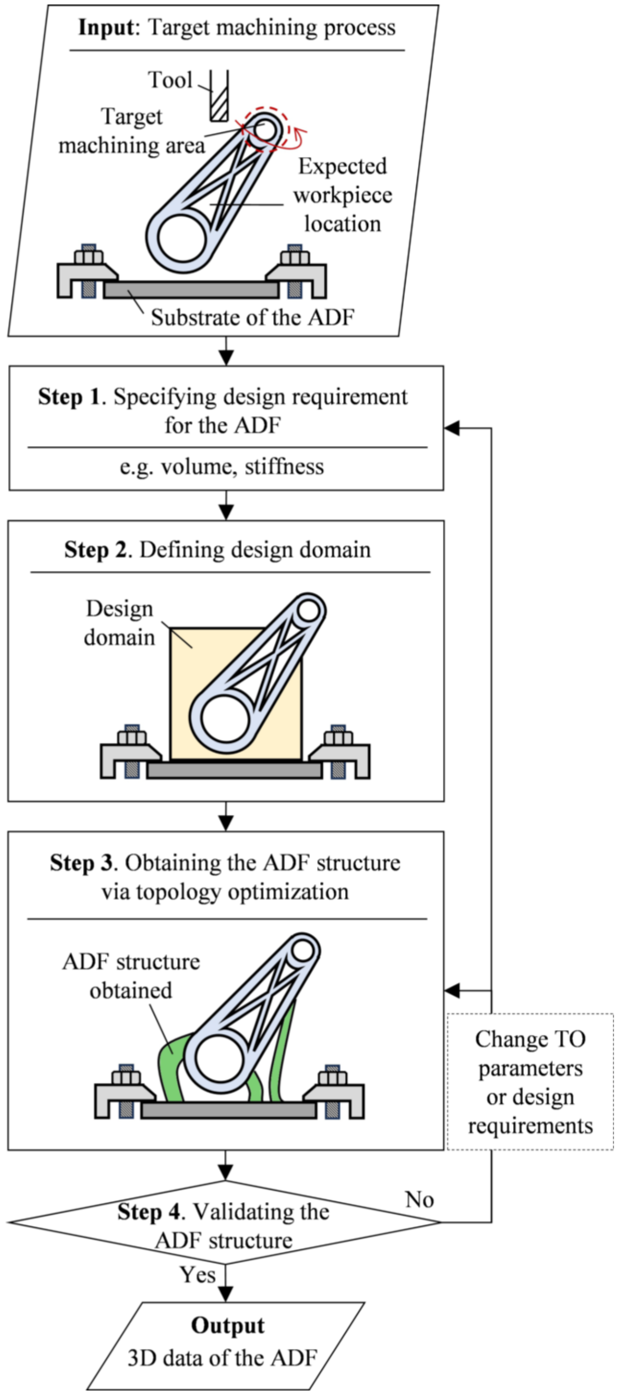


Fig. 2. Design method of ADF using TO.

its ability to machine workpieces that would otherwise be impossible to machine using conventional fixtures. This advantage can lower manufacturing constraints related to post-processing, potentially enabling enhanced component performance and weight reduction through improved design freedom.

2.2. Design Method of ADF

The ADF design method is illustrated in **Fig. 2**. Before designing an ADF, it is necessary to define the target machining process, including the specifications of the target

Table 1. Design requirements for ADF.

Design requirement	Detailed description
Adhesive strength requirement	The destruction of the adhesive layer against the cutting forces should not occur.
Displacement requirement	The displacement of the workpiece against the cutting forces should be lower than the tolerance value.
Weight requirement	The weight of the ADF should be lower than the tolerance value.

machining area, process parameters, tool path, and the expected location of the workpiece to be fixed. This information serves as the foundation for the subsequent steps. The following sections describe each step of the design method.

Step 1. Specifying the design requirements for ADF

As in normal design processes, the design requirements for ADF are specified first. In particular, for ADF, the requirements listed in **Table 1** should be incorporated. The adhesive strength and displacement requirements are necessary to ensure successful machining. The weight requirement is also important in addressing potentially high manufacturing costs of ADF with PBF.

The positioning performance of the workpiece, which is a typical design requirement for conventional fixtures, does not need to be addressed in the design of the ADF. This is because all the surface geometries of PBF workpieces inherently contain deviations from their ideal geometries, making it difficult to accurately locate the PBF workpiece within an existing coordinate system. Furthermore, the manufacturability of ADF was ignored in this study because PBF has a relatively lower manufacturing constraint than other manufacturing methods, and the implementation of PBF manufacturability in TO is not the core focus of this study.

Step 2. Defining design domain

The ADF structure can be distributed within the design domain that is defined in this step. The design domain should be connected to the workpiece because contact between the ADF and workpiece is required. In addition, the design domain should not interfere with the trajectories of machine tool elements (e.g., tools and spindles) during the target machining process.

Step 3. Obtaining the ADF structure via TO

TO is a method for designing structures by maximizing or minimizing a specified objective function while satisfying prescribed constraints. In this study, for the simplicity of implementation and computational efficiency, the TO design of the ADF structure maximizes the static stiffness under the weight requirement. Specifically, the objective function is the mean compliance against multiple static forces representing the expected cutting forces during the target machining process. The minimization problem of the mean compliance is then solved under the weight requirement to obtain the ADF structure. A mathematical description of TO used in this study is presented in Section 2.4.

Step 4. Validating the ADF structure

This step involves verifying whether the design requirements that were not explicitly introduced in the previous TO were satisfied. If the design requirements are not satisfied, either the parameters in the TO should be modified or the design requirements should be revised, and the TO is executed again. Although this iterative method of finding an ADF structure that satisfies all the design requirements may not be a truly intelligent approach, it should be more practical than introducing all the design requirements into TO simultaneously. Otherwise, the computation may not converge or impractical structures may be generated because of the complexity of TO. Therefore, it is more effective to find an ADF structure that satisfies all the design constraints by repeating the common TO with some of the design constraints introduced.

The designed ADF is printed by PBF and assembled with the workpiece to perform the target machining process. For assembly, it is crucial to consider the influence of shape accuracy, which arises from printing errors inherent in PBF that may hinder proper assembly. One method to ensure the assembly is to offset the adhesive surfaces of the ADF to create a gap between the ADF and workpiece. Because this gap is introduced to prevent undesired interference caused by printing errors, the offset value can be set to the expected printing error value.

2.3. Practical Modification of the ADF Design Method

As described in Section 2.2, once the target machining process is established, the ADF structure can be semi-automatically designed using TO. However, the following considerations must be made when using TO in the ADF design.

The first consideration is the assembly process of the workpiece and ADF. Because the ADF is designed via TO under physical conditions during the target machining process, the assembly process of the workpiece and ADF are not considered during TO. Consequently, interference between the workpiece and ADF may occur, thereby hindering the assembly. To address this problem, the domain along the movement path of the workpiece during assembly should be excluded from the ADF design domain. In this study, the movement path of the workpiece is predetermined, in addition to the input information of the target machining process. It is generally better to assemble the workpiece by inserting it from its narrower part to minimize the domain to be excluded and increase the design domain and adhesive area. The domain excluded from the design domain is referred to as the workpiece passage domain.

The next important consideration is the trade-off relationship between the adhesive strength and weight require-

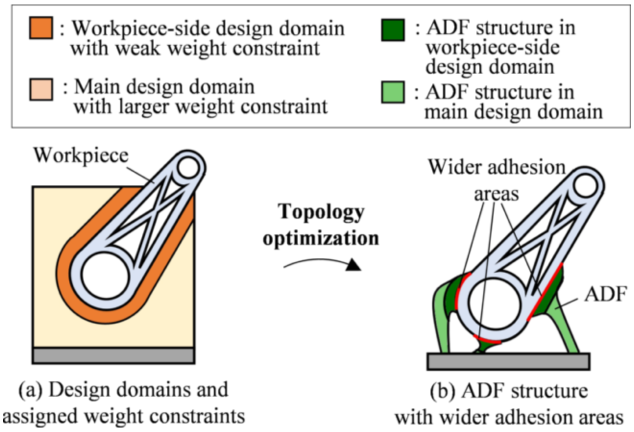


Fig. 3. Different weight constraints introduced into divided design domains to simultaneously satisfy weight and adhesive strength requirements.

ments. The weight requirement in TO restricts the adhesion location and area between the workpiece and ADF, which in turn affects the fulfillment of the adhesive strength requirement. In general, the weight constraint in TO is set uniformly across the entire design domain and cannot handle this tradeoff relationship. To address this issue, as shown in **Fig. 3**, the design domain is divided into a domain close to the workpiece (workpiece-side design domain) and the remaining design domain (main design domain). By setting different weight constraints for each domain, the adhesion location and area can be modified without changing the overall weight of the ADF. This can contribute to the efficient determination of an ADF structure that satisfies both requirements. The thickness of the workpiece-side design domain was preferably small to ensure a large main design domain, which contributed significantly to the overall stiffness of the ADF. Specifically, a thickness of approximately one to a few millimeters is advisable. Considering that the difference in Young's modulus between the metal and adhesive is approximately 100 times, a thickness in this range should provide sufficient relative stiffness to the adhesive layer.

2.4. TO for Designing ADF Structure

The present method is based on the level-set method using the reaction–diffusion equation (RDE), as demonstrated by Yamada et al. [23] and Otomori et al. [24]. The description overlapping with these studies are briefly discussed.

Figure 4 illustrates the design domains, boundary conditions, and material domain of the TO. The adhesive between the workpiece and the ADF was ignored for simplicity of implementation. In the level-set method, the material boundaries within the design domain are represented by iso-surface of level-set function ϕ, as follows:

$$\begin{cases} 0 \le \phi(x) \le 1 & \forall x \in \Omega \setminus \partial\Omega \\ \phi(x) = 0 & \forall x \in \partial\Omega \\ -1 \le \phi(x) < 0 & \forall x \in \left(D_{\mathrm{ws}} \cup D_{\mathrm{m}}\right) \setminus \Omega \end{cases}, \tag{1}$$

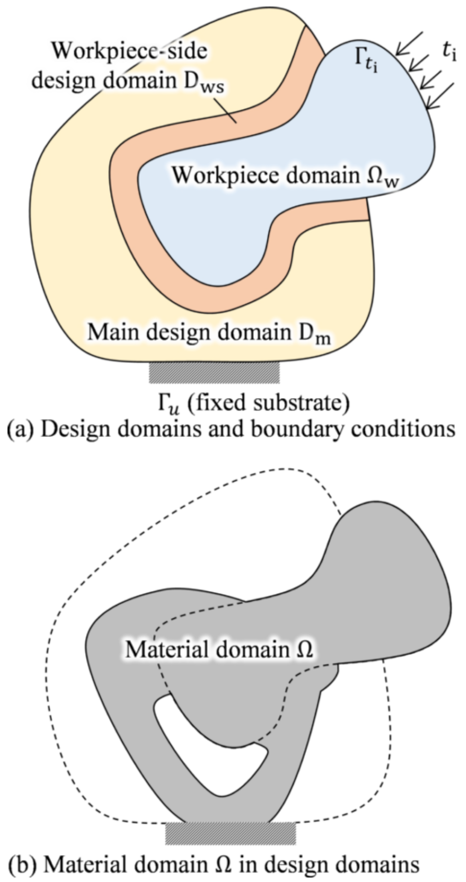


Fig. 4. Design domains, boundary conditions, and material domain in the TO for designing a ADF structure.

where Ω is the material domain, "\" represents the set difference, $\partial\Omega$ is the boundary of the material domain, Ω_{w} is the workpiece domain, D_{ws} is the workpiece-side design domain, and D_{m} is the main design domain. The value of level-set function ϕ within Ω_{w} is always set to 1 because Ω_{w} is the given structure outside the design domains.

The objective function of TO is the average mean compliance for each static-force case representing the expected cutting force. By introducing the weight requirement of the ADF (described as volume constraints), the optimization problem for the ADF structure can be formulated as follows:

$$\min_{\phi} \quad F\left(\chi_\phi\right) = \frac{1}{m}\sum_{\mathrm{i}=1}^{\mathrm{m}} \int_{\Gamma_{t_\mathrm{i}}} \boldsymbol{t}_\mathrm{i} \cdot \boldsymbol{u}_\mathrm{i} d\Gamma, \tag{2}$$

$$\text{s.t.} \quad a\left(\boldsymbol{u}_\mathrm{i}, \boldsymbol{v}\right) = l_\mathrm{i}\left(\boldsymbol{v}\right), \tag{3}$$

$$G_{\mathrm{ws}}\left(\chi_\phi\right) = \int_{D_{\mathrm{ws}}} \chi_\phi d\Omega - V_{\mathrm{max}_{\mathrm{ws}}} \le 0, \tag{4}$$

$$G_{\mathrm{m}}\left(\chi_\phi\right) = \int_{D_{\mathrm{m}}} \chi_\phi d\Omega - V_{\mathrm{max}_{\mathrm{m}}} \le 0, \tag{5}$$

where χ_ϕ is the smoothed Heaviside function of ϕ, m is the total number of the force cases, $\boldsymbol{t}_\mathrm{i}$ is the static force vector for each force case, $\boldsymbol{u}_\mathrm{i}$ is the displacement vector caused by $\boldsymbol{t}_\mathrm{i}$, G_{ws} and G_{m} are volume constraints for D_{ws} and D_{m}, respectively, and $V_{\mathrm{max}_{\mathrm{ws}}}$ and $V_{\mathrm{max}_{\mathrm{m}}}$ are the maximum volume

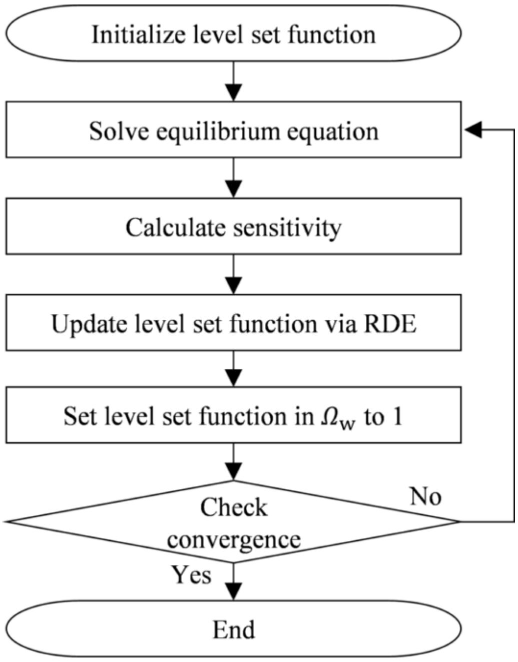


Fig. 5. Flowchart of the steps involved in TO for designing an ADF structure.

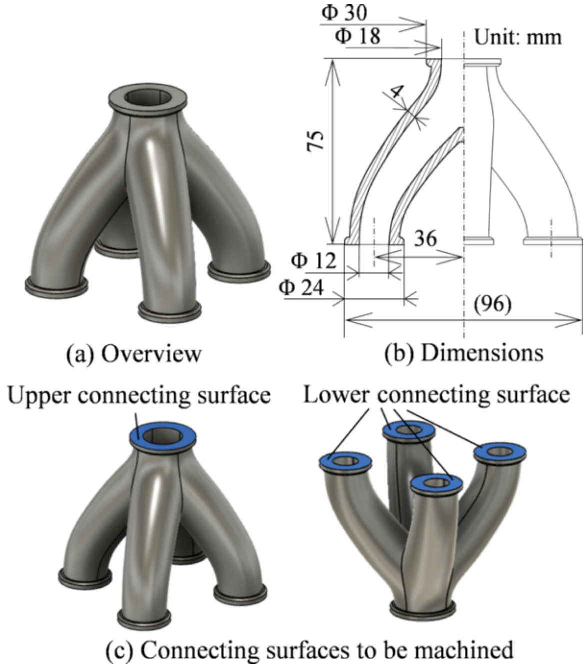


Fig. 6. Target workpiece and its connecting surfaces to be machined in the post-process.

of ADF structure in D_{ws} and D_m, respectively. Eq. (3) expresses the weak form of the equilibrium equation for each force case, and the notations in the equations are defined as:

$$a\left(\boldsymbol{u}_i, \boldsymbol{v}\right) = \int_{\Omega_w \cup D_{ws} \cup D_m} \boldsymbol{\varepsilon}\left(\boldsymbol{u}_i\right) : \boldsymbol{E} : \boldsymbol{\varepsilon}(\boldsymbol{v})\, \chi_\phi d\Omega, \quad (6)$$

$$l_i(\boldsymbol{v}) = \int_{\Gamma_{t_i}} \boldsymbol{t}_i \cdot \boldsymbol{v} d\Omega, \quad (7)$$

where $\boldsymbol{\varepsilon}$ is the linearized strain tensor, $\boldsymbol{E}$ is the elasticity tensor, and $\boldsymbol{v}$ is the test function for the weak form. The operation ":" in Eq. (6) represents the tensor product, where the stress tensor $\boldsymbol{\sigma}$ is expressed as $\boldsymbol{\sigma}(\boldsymbol{v}) = \boldsymbol{E} : \boldsymbol{\varepsilon}(\boldsymbol{v})$. Eqs. (6) and (7) are also known as the principles of virtual work.

To obtain an optimal solution, the level-set function was updated by solving the following RDE:

$$\frac{\partial \phi}{\partial t} = -K\left(\overline{F}' - \tau \nabla^2 \phi\right), \quad (8)$$

where K is the coefficient of proportionality, $\overline{F}'$ is the design sensitivity of the above optimization problem, and τ is the coefficient of regularization, which can be adjusted to control the complexity of the shape. $\overline{F}'$ can be derived using the adjoint variable method.

A flowchart of TO for the ADF structure is shown in **Fig. 5**. First, the level-set function is initialized. Second, the equilibrium equations for each force case are solved to obtain the displacement vectors. Subsequently, the design sensitivity is calculated using the obtained displacement vectors. The level-set function is then updated via the RDE with the calculated sensitivity. The level-set function inside the workpiece domain Ω_w is set to 1, indicating the existence of material. Finally, the updated level-set function is compared with the previous one, and if the change is larger than the convergence criterion, the same procedure is repeated until the level-set function converges; otherwise, the optimization is terminated. The structures in the design domains D_{ws} and D_m are the final designs of the ADF structure.

3. Case Study

3.1. Target Workpiece and Post-Process

The ADF design method was validated through a case study of a manifold workpiece shown in **Fig. 6**. The top and bottom surfaces of the workpiece shown in **Fig. 6(c)** were finished by machining and are referred to as the upper and lower connecting surfaces, respectively. **Fig. 7** shows the entire workpiece manufacturing process. First, the workpiece was printed using PBF in the build orientation shown in **Fig. 7(a)**, using the printing method and powder materials listed in **Table 2**. Post-processing involves the following steps: (1) wire cutting to remove the substrate from the printed workpiece, as shown in **Fig. 7(b)**, and (2) machining of the contact surfaces of the workpiece, as shown in **Fig. 7(c)**. The machining process was performed using a 5-axis machining center. As the first step in the machining process, the workpiece was fixed with its lower connecting surface facing the front. Subsequently, the *B*- and *C*-axes of the machining center were rotated, and the upper connecting surface was machined. Subsequently, the *C*-axis was rotated again, and the lower connecting surfaces were machined. An ADF was designed using the proposed design method to fix the workpiece during the machining

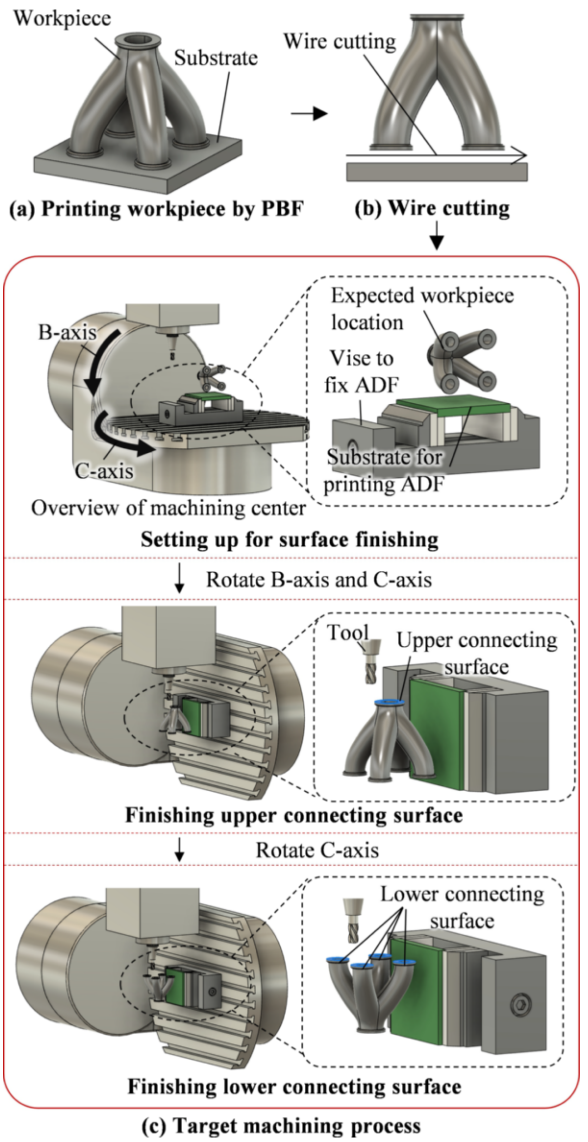


Fig. 7. Post-processes for the target workpiece (an ADF was designed for the finishing process of the connecting surfaces).

Table 2. Printing method and material of PBF powder used in the case study.

Printing method	Selective laser melting
Material of PBF powder	SUS316L (JIS G 4303)

process.

The geometry of the workpiece presents a challenge for its fixation. This is because the upper and lower surfaces to be machined face each other, and the side surfaces have geometries that are difficult to fix. It may be possible to perform the target machining process using conventional fixtures. However, considering the time required for fixture design, manufacturing costs, and the need for design experience, using ADF might be more efficient. Furthermore, the upper and lower connecting surfaces would be normally machined under different setups with several fixtures. Therefore, the high degree of freedom offered by

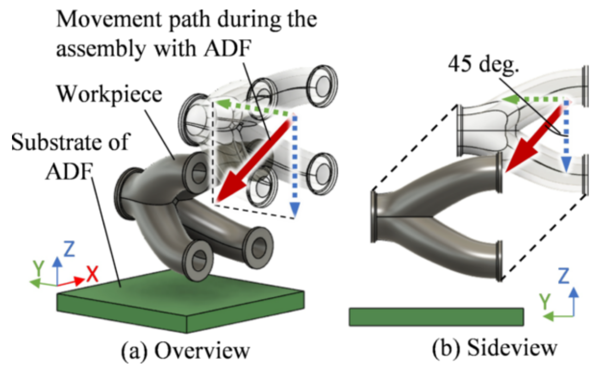


Fig. 8. Movement path of the workpiece determined during the assembly with the ADF.

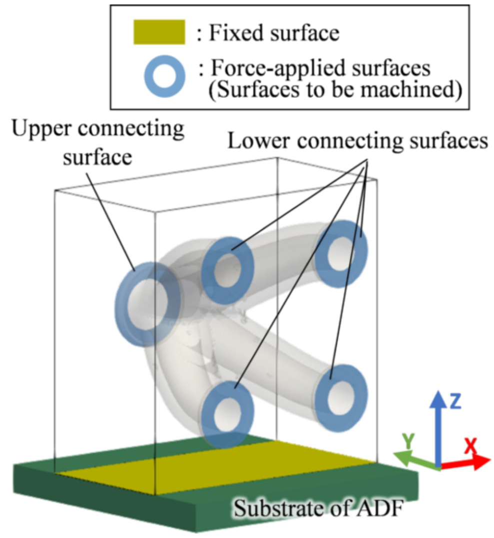


Fig. 9. Fixed surface and force applied surfaces.

ADF in terms of the fixture location and orientation of the workpiece allows the integration of machining processes for the upper and lower connecting surfaces. This demonstrates the potential of ADF to enhance the flexibility of the machining process, thereby reducing the need for multiple setups and fixtures.

3.2. Designing of the ADF Using the Proposed Design Method

3.2.1. Input Information

Before designing the ADF, the input information was defined as follows. First, a 100×100 mm SUS316L plate was selected as the substrate for printing the ADF. Second, the movement path of the workpiece relative to the ADF substrate was determined, as shown in **Fig. 8**. The workpiece was assembled in a straight line at a diagonal angle with respect to the ADF substrate. In addition, the static force cases representing the cutting forces during the target machining process were determined, as shown in **Fig. 9** and listed in **Table 3**. Four static force vectors were applied individually to each of the five connecting surfaces. The same static force vectors were applied to the four surfaces of the lower connections. The forces applied to the lower

Table 3. Static-force vectors representing the expected cutting forces during the target machining process (these forces were individually applied to the connecting surfaces in TO. The axes of the vectors correspond to the XYZ axes in **Fig. 9**).

Applied to lower connecting surfaces [N]	$(44,\ 33,\ 11)^T$
	$(-11,\ 33,\ 44)^T$
	$(-44,\ 33,\ -11)^T$
	$(11,\ 33,\ -44)^T$
Applied to upper connecting surface [N]	$(-44,\ -33,\ 11)^T$
	$(11,\ -33,\ 44)^T$
	$(44,\ -33,\ -11)^T$
	$(-11,\ -33,\ -44)^T$

Here, T denotes the transpose.

Table 4. Cutting conditions.

Tool	R5 2-blade ball endmill
Feed rate [mm/min]	180
Spindle rotation speed [rpm]	2200
Axial depth of cut [mm]	0.25
Radial depth of cut [mm]	0.5

Table 5. Specifications of the adhesive.

Adhesive material	Epoxy
Young's modulus [GPa]	2.4
Tensile strength [MPa]	13.9

and upper connecting surfaces were symmetrical about the X–Z plane. The magnitudes and directions of the static force vectors were based on the cutting forces measured in a preliminary experiment under the cutting conditions listed in **Table 4**. Finally, an adhesive with the specifications presented in **Table 5** was selected to fix the workpiece and the ADF.

3.2.2. Design Requirements for ADF

As discussed in Section 2.2, the ADF must satisfy the adhesive strength, displacement, and weight requirements. Each requirement was specified as follows. The adhesive strength requirement was defined to ensure that the tensile stress within the adhesive was below the tensile strength of the adhesive. The displacement requirement was defined to ensure that the magnitude of the maximum displacement of the surface to be machined was < 2.0 µm. The weight requirement of ADF, excluding the substrate, was determined to be 970 g.

3.2.3. Design Domain Definition

The design domain was defined as shown in **Fig. 10**, avoiding collisions with the tool trajectories and ensuring the assembly process with the workpiece. Initially, the design domain was set as a cubic domain surrounding the workpiece, with the same dimensions as the footprint of

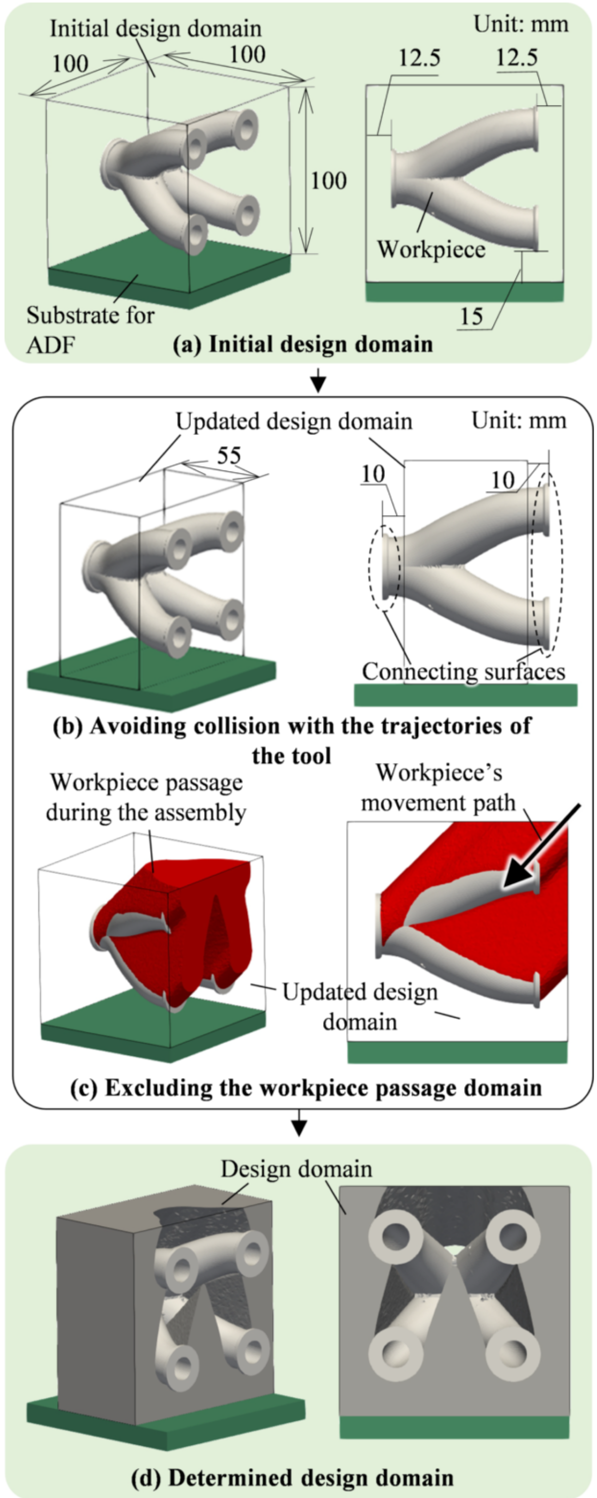


Fig. 10. Definition flow of the design domain for the ADF.

the substrate, as shown in **Fig. 10(a)**. To avoid tool collision, the domains around the upper and lower connecting surfaces were excluded from the initial design domain to obtain a 10 mm clearance from the surfaces, as shown in **Fig. 10(b)**. To ensure the assembly process, the workpiece passage domain was excluded from the initial design domain, as illustrated by the red domain in **Fig. 10(c)**. The common part of both the updated design domains is the

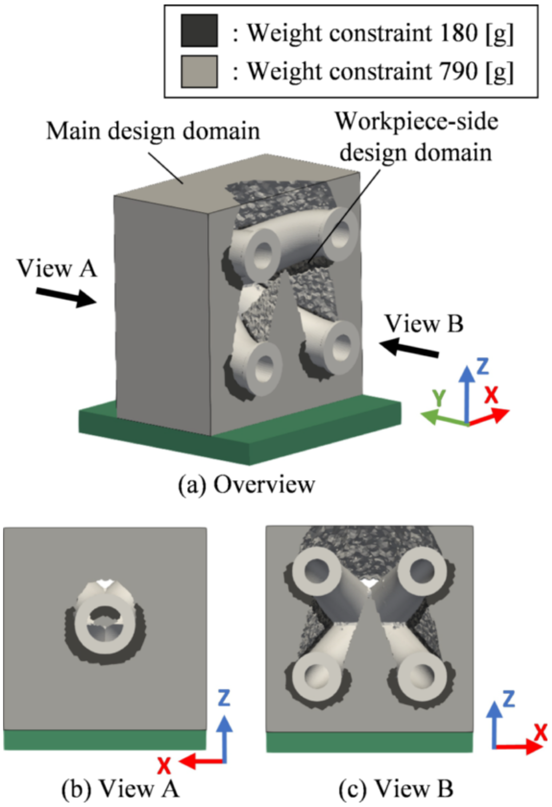


Fig. 11. Divided design domains and assigned weight constraints in TO.

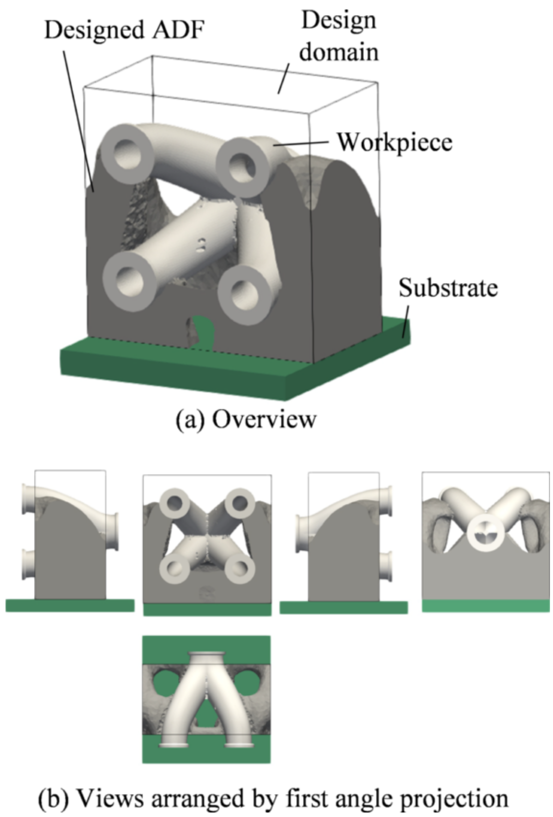


Fig. 12. ADF Structure obtained by TO.

final design domain, which is shown as a gray domain in **Fig. 10(d)**.

3.2.4. ADF Structure via TO

As explained in Section 2.3, the weight constraints in TO were set separately for the two design domains. In this case study, the thickness of the workpiece-side design domain is 4 mm, as illustrated in **Fig. 11**. The weight constraint for the workpiece-side design domain was set to 180 g, and that for the main design domain was set to 790 g, limiting the entire weight of the ADF within the weight requirement.

The TO, which is defined in Section 2.4, was solved by finite element method to design the ADF structure. The resulting ADF structure is illustrated in **Fig. 12**.

3.2.5. Validation of the ADF Structure

The ADF structure was validated by checking whether all the design requirements were satisfied. For the validation considering adhesive properties, adhesive layers with the specifications in **Table 5** were introduced between the ADF and workpiece. The thicknesses of the adhesive layers were set to the expected PBF printing errors. Based on a prior study that showed that PBF printing errors were generally less than 1 mm [25], adhesive layers of thickness 1 mm were introduced between the ADF and workpiece.

The fulfillment of the adhesive strength requirement was validated by comparing the tensile strength of the adhesive with the tensile stress in the adhesive layer, which was calculated through an additional structural analysis. The calculated maximum tensile stress in the adhesive layers was 2.40 MPa, which was smaller than the tensile strength of the adhesive. Thus, the adhesive strength requirements were satisfied. Similarly, the displacement requirement was also verified. The workpiece displacement for the defined force cases was calculated and the maximum displacement of the machined surface across all force cases was obtained. The calculated maximum displacement of the machined surface was 1.58 μm, which is below the displacement requirement of 2.0 μm. Finally, because the weight requirement is explicitly incorporated within the TO, the resulting ADF structure inherently satisfies the weight requirement. Consequently, the structure illustrated in **Fig. 12** was determined to be the final ADF structure.

4. Post-Processing with the Designed ADF and Discussion

To validate the ADF designed using the proposed method, post-processing with ADF was performed. The workpiece and ADF were printed using PBF with the materials listed in **Table 2**. The workpiece and ADF were fixed together using the adhesives specified in **Table 5**. Subsequently, a cutting experiment was conducted under the cutting conditions listed in **Table 4**.

Figure 13 shows an ADF printed using PBF. The support structure was manually removed after printing. **Fig. 14** shows the ADF and the workpiece assembled using

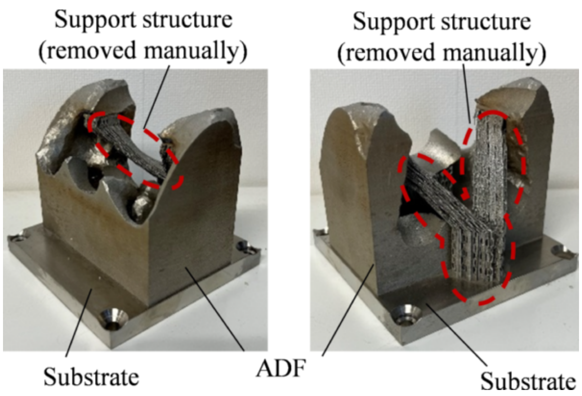


Fig. 13. ADF with the support structure printed by PBF.

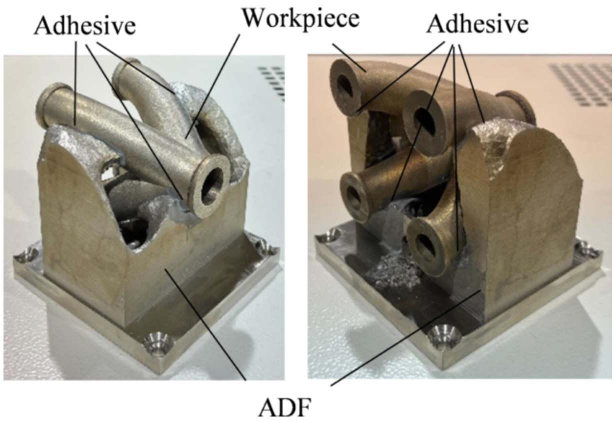
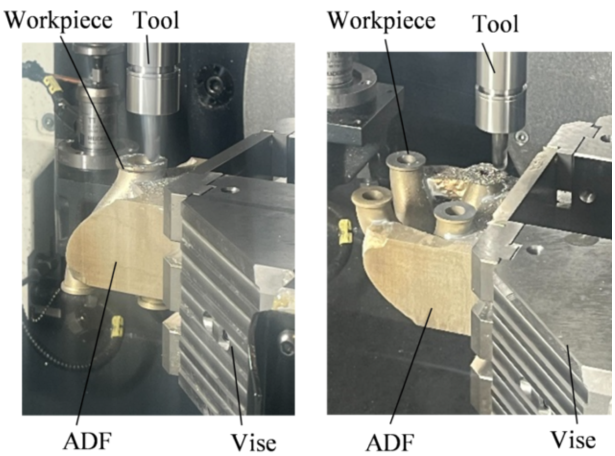


Fig. 14. Assembled ADF and the workpiece with the adhesive.

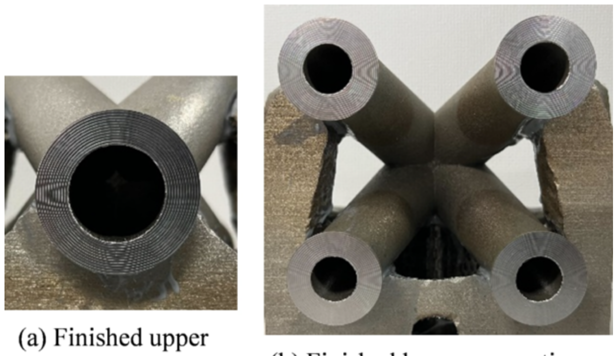


(a) Finishing upper connecting surface

(b) Finishing lower connecting surface

Fig. 15. Post-processes with the printed ADF.

the adhesive. **Fig. 15** shows the post-processes involved in finishing the upper and lower connecting surfaces. The finished surfaces are shown in **Fig. 16**. The post-processes were successfully accomplished without the destruction of the adhesive. The case study confirmed that the proposed design method can provide a practical ADF for machining PBF workpieces without requiring special knowledge for designing the fixtures. Although the case study focused on



(a) Finished upper connecting surface

(b) Finished lower connecting surfaces

Fig. 16. Finished connecting surfaces.

a manifold workpiece, the proposed design method can be applied to workpieces with different shapes.

However, the case study revealed several areas for improvement in the ADF design method and its manufacturing process. First, incorporating PBF manufacturing constraints, such as a support-free constraint and an overheating prevention constraint, into TO is crucial for reducing the post-processes for PBF-manufactured ADFs, which were ignored in this case study for simple implementation. Second, more attention should be paid to the manufacturing accuracy of PBF. A low PBF manufacturing accuracy may hinder the assembly of the workpiece and ADF or create excessive gaps between them. Although the adhesive could tolerate these gaps to a certain extent and fix them together, the stiffness of the assembled structure may differ from the predicted value. Furthermore, the use of adhesives inevitably introduces additional time to fix and rework the process chain. However, the proposed method has the potential to reduce the time required for fixture design. To accurately compare the time efficiency of the proposed method with that of the traditional approach, further research is required to conduct the same post-processes using both a fixture designed by an operator and an ADF designed using the proposed method.

5. Conclusion

This study addressed the difficulty of fixturing PBF workpieces with low stiffness and geometrical complexity. To facilitate fixation, this study introduced an ADF that uses adhesives to fix the workpiece and was manufactured by PBF. To avoid laborious and operator-dependent processes in the design of ADF, a design method based on TO was proposed to satisfy the design requirements of ADF. The design domain for TO was restricted to ensure the assembly of the ADF and workpiece. Different weight constraints were set for the divided design domains to efficiently satisfy the adhesive strength and weight requirements. A case study was conducted using a manifold workpiece to validate the effectiveness of the proposed design method.

In the case study, the ADF designed using the proposed method successfully enabled the fixation of the workpiece in the target machining processes. However, the case study revealed several areas for improvement in the design of ADF and its manufacturing process, such as incorporating PBF manufacturing constraints into TO, investigating the effect of PBF manufacturing accuracy on ADF performance, and comparing the time efficiency of the proposed method with that of traditional fixture design approaches. Addressing these aspects will refine the ADF design method and provide a more robust and efficient solution for post-processing PBF workpieces.

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