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Knowledge-Based Assistance System for Part Preparation in Additive Repair by Laser Powder Bed Fusion

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Abstract

For the economic use of repair in the spare parts business, additive repair by Laser Powder Bed Fusion (LPBF) is a promising technology. As material can only be applied to a flat surface in LPBF, prior machining is required. The selection of the section plane requires expert knowledge, though. To provide that knowledge and recommend a suitable section plane, an expert system can be used. In this paper, a concept for such an expert system is presented and its functionality is evaluated by an example.

Keywords: additive manufacturing, additive repair, decision making, knowledge-based engineering (KBE), laser powder bed fusion (LPBF)

1. Introduction

Part of the necessary transformation from a linear economy to a resource-efficient circular economy is to extend the lifespan of existing products and components through their repair in the event of damage. For an economical repair of components, the use of automated additive manufacturing (AM) processes is highly promising. In so-called additive repair, the processes of the Direct Energy Deposition (DED) group, Laser Powder Bed Fusion (LPBF) and Cold Spray (CS) are applied (Wasono et al., 2019; Li et al., 2017; Zghair and Lachmayer, 2017). LPBF is particularly suitable for the repair of components with complicated, filigree structures or internal channels, e.g. gas turbine combustors (Andersson et al., 2017).

Before the material is applied by LPBF, the component must be prepared, i.e. a plane is machined. The position and orientation of the created plane affect the duration, cost and quality of the repair. The determination of a suitable section plane requires additive repair expertise, as there are numerous aspects resp. criteria which influence the suitability of a section plane and may conflict with each other. Thus, the efficiency of the repair depends on the know-how of the available employees. In order to ensure a time and cost-efficient repair process chain and to achieve a high quality of the repair, it is reasonable to support and automate the determination of the section plane with a system that provides the necessary expert knowledge.

This paper presents a software concept for an assistance system that recommends a section plane based on the CAD data of a damaged part. Since usually only the CAD model of the undamaged part is available, users first extrude therein a cuboid that represents the damaged part areas. Based on this, the knowledge-based engineering system (KBES) generates a number of potentially suitable section planes and compares them for their suitability in order to identify the most suitable plane. The system creates the necessary models for the subsequent steps in the additive repair process chain according to the selected section plane.

For this purpose, the methodological approach "Methodology and tools Oriented to Knowledge-based engineering Applications" (MOKA) according to Stokes (2001) was followed. As part of its first phase, the requirements for the choice of the section plane were collected. These are summarized in the following section. Moreover, in the theoretical background, expert systems are presented and their previous use to support the additive repair process. In section 3, the specification of the assistance system is presented first and its implementation is explained in the following. The evaluation of the developed assistance system is described in section 4.

2. Theoretical Background

2.1. Additive repair by LPBF

A typical process chain for repairing a component using LPBF is shown in Figure 1. First, it is determined which areas of the component are damaged, what type of damage is present and to what cause the damage can be attributed. In the following, the damaged component is prepared as well as the data for the additive material application. A requirement for the LPBF process is that the layer-by-layer material application is performed on a planar surface of the component. This section plane is prepared by milling as part of the component preparation. In general, a single plane surface is created. However, section plane profiles composed of two or more planes are also possible, as proposed by Zghair and Lachmayer (2017). But so far, such section plane profiles have not been used for component repair. A major drawback is that the duration, resource input, and complexity of the repair process are significantly increased as material is applied to each plane in a separate process step. For example, the component must be manually aligned, sunk into the powder bed and the inert gas atmosphere must be generated for each manufacturing step (Zghair and Lachmayer, 2017).

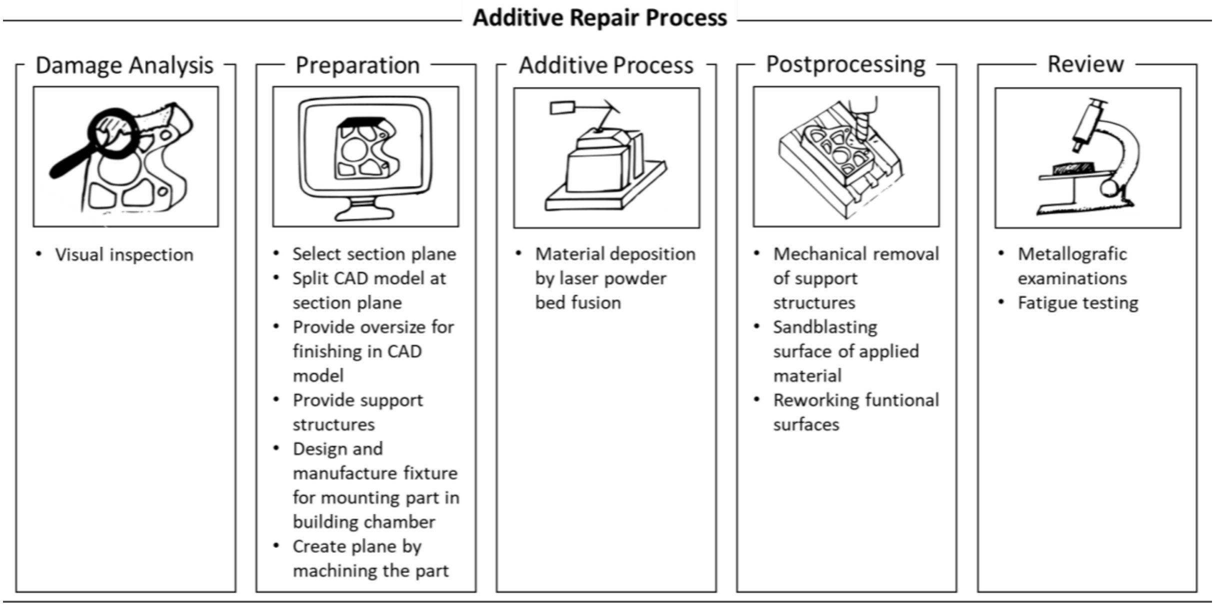


Figure 1. Exemplary additive repair process, according to Ganter et al. 2022

The decision on the section plane influences the technical feasibility, the economic and ecological sustainability of the repair as well as the quality of the repaired component, e.g. as it determines the necessary post-processing effort and the volume to be applied. The difficulty in determining the section plane is that a large number of aspects influences the suitability of a plane, sometimes even contradictory to each other. To those belong:

- The entire damaged volume should be removed through the section plane, e.g. corroded material or plasticized component areas. A clearance distance can be provided between the section plane and the damaged component area.

- The minimum amount of undamaged material should be removed to produce the section plane. In particular, no undamaged functional surfaces should be removed that require reworking. Additionally, the height of the structure to be built up should be as low as possible. The volume and, especially, the height significantly influence the duration of the additive material application and the resource input, e.g. powder material.
- The repair process allows the material or the shape of a component to be modified with the aim of improving existing functions or realizing new functions. To modify existing functions or implement additional ones in a so-called additive refurbishment, the corresponding component areas must be removed during component preparation (Ganter et al., 2021a).
- The position of the section plane should be chosen in such a way that a suitable starting surface for the LPBF process is created without too thin edges (Andersson et al., 2017).
- Zghair and Lachmayer (2017) emphasize that the choice of the section plane should take into account the component stresses in service, especially if the mechanical properties of the material applied in LPBF and the base component differ.
- The orientation of the section plane must be selected so that the component fits into the limited installation space of the LPBF system and the desired dimensions can be produced.
- The orientation of the section plane determines the build-up direction in the LPBF process. The build-up direction is decisive for a number of LPBF restrictions, which determine the postprocessing effort in particular. These restrictions include the necessity of support structures for the production of overhangs above a certain length. If possible, support structures should be avoided because they increase the cost and ecological impact of the additive process. On the one hand, they have to be removed during post-processing and leave undesirable traces on surfaces which often have to be removed by machining. On the other hand, support structures increase the amount of powder material used in the LPBF. In addition, in the additive repair process, support structures often require a special fixture for the component, which provides a platform on which support structures can be built up. This significantly increases the complexity of fixture design. If support structures cannot be avoided, Granvallet et al. (2020) suggest to select a build-up direction which allows support structures to be built up on functional surfaces which have to be reworked anyway. Besides the necessity of support structures, the orientation of the section plane affects the roughness of surfaces. In order to achieve a low roughness of surfaces that do not necessarily require reworking, they should be oriented horizontally or vertically to the build-up direction. If surfaces are manufactured at an inclination to the build direction, they will have a poorer surface quality due to the so-called stair-step effect (Thomas, 2009; Kranz, 2017). Furthermore, the minimum edge radius that can be manufactured also depends on the orientation of the component in the build space. In the build direction, the minimum edge radius is limited by the focal diameter (Kranz, 2017). Moreover, the microstructure and the mechanical properties of additively manufactured structures are usually anisotropic in dependence of the build direction (Kok et al., 2018).
- From previously mentioned aspects it results that the section plane in additive repair should not intersect any holes. The functional surfaces should always be manufactured as a whole in order to meet the required tolerances and to avoid support structures as well as complex fixtures.

This list shows that the decision on the section plane is a problem that requires the consideration of numerous criteria. For many components, conflicting design goals arise in this context. An additional challenge for decision makers is that many criteria are difficult to evaluate visually or manually, e.g. the undamaged volume removed by a section plane or the required support structures in the following LPBF process.

2.2. Knowledge-based systems

Knowledge-based systems (KBS) can be used to solve complicated problems with the help of artificial intelligence. These use digitally presented expert knowledge and simulate the procedure of an expert in order to perform a solution process (Milton, 2008). Knowledge-based systems are composed of three main components: the knowledge base for storing expert knowledge, the inference engine for linking the knowledge and an interface to the environment (Hopgood, 2012).

Knowledge-based engineering systems (KBES) are considered as a special form of a KBS, which can be integrated into a CAD system (Verhagen et al., 2012). In the CAD system, expert knowledge can be stored by rules or in tabular form, e.g. design rules and standard parts catalogues (Hirz et al., 2013). An advantage of KBES is the easy extensibility of the knowledge base, so that information can be added or changed quickly (Milton, 2008; Skarka, 2007). KBES are used for the synthesis of design artefacts. CAD models are configured according to input parameters defined by the user in a user interface and all stored design rules, standards and norms (Gembarski, 2020). Besides, KBES are used for the automatic analysis and evaluation of CAD designs. Here, the system input is a finished CAD model instead of individual parameters. To analyze this design, either the geometry can be read out and abstracted into parameters or the design history in form of the structure tree can be evaluated. Subsequently, the inference engine compares the design with the knowledge base, e.g. to check for conformity to standards and compliance with restrictions (Hoppe et al., 2021).

2.3. Expert systems for additive repair

Various expert systems have already been presented in the literature to support the additive repair process. Several authors address the process planning for additive repair using DED. For example, Arntz et al. (2015) developed a system for computer aided manufacturing process planning for wire-based laser deposition welding. Therein, the laser path is determined based on the geometry of the machined part, which is digitized by a laser scanning process. Perini et al (2020) presented a system that generates the volume model for the direct laser deposition process from the 3D scan of a damaged part. A part preparation is not included in their described procedure so far. A system that identifies a suitable additive process for the repair of a damaged part through rule-based reasoning is presented by Ganter et al. (2022). In addition, the system recommends an appropriate repair process chain through case-based reasoning using a knowledge base from successful use cases of additive repair.

Furthermore, expert systems have been presented which check the alignment of components to Design for AM guidelines and help in process planning for AM. For example, Mbow et al. (2021) present a knowledge-based methodology for the evaluation of potential part orientations for the LPBF process. The potential part orientations are evaluated for their conformity with action rules by means of a desirability function. Zhang et al. (2019) have developed a system that includes the functions to optimize the build orientation of a part geometry and to help detect critical geometric features for the AM process (small openings, thin features, sharp corners, thin-to-thick transitions). For the latter, the part is divided into layers and the critical features are detected per layer.

Systems that depict the LPBF restrictions to support AM are not suitable for the additive repair process, as they do not contain the most relevant action rules for additive repair. One of these is that as little undamaged material as possible is removed by the section plane. Furthermore, these include that undamaged functional surfaces, such as holes, are not cut and that component areas to be replaced in additive refurbishment are removed by the section plane. This paper addresses the gap of a missing support for the choice of the section plane in repair processes by LPBF. For this purpose, domain-specific knowledge about additive repair was formalized and a concept for an expert system was developed that recommends a suitable section plane based on the CAD model.

3. Assistance system for part preparation in additive repair by LPBF

To develop the assistance system, the requirements were first defined. For this purpose, the relevant aspects were prioritized for the selection of the section plane. The use case diagram in Figure 2 summarizes which aspects were prioritized as most important and implemented in the assistance system. The diagram also summarizes which steps of the additive repair process chain are automated by the assistance system.

According to the requirements, a KBES implemented in a CAD program was chosen. The integration in a CAD program allows to select the section plane based on the analysis of existing features, e.g. holes. It further allows the identification of functional surfaces either by surface information and tolerances stored in the CAD model or through the user's selection of the functional surfaces in a user interface. Moreover, for the selection of the section plane, additional features can be added to the model, e.g. representing damaged part areas. Furthermore, the implementation in a CAD program allows to adapt the model before it is output for the additive process. This is necessary, for example, to provide an oversize on functional surfaces for rework or to modify the design for an additive refurbishment.

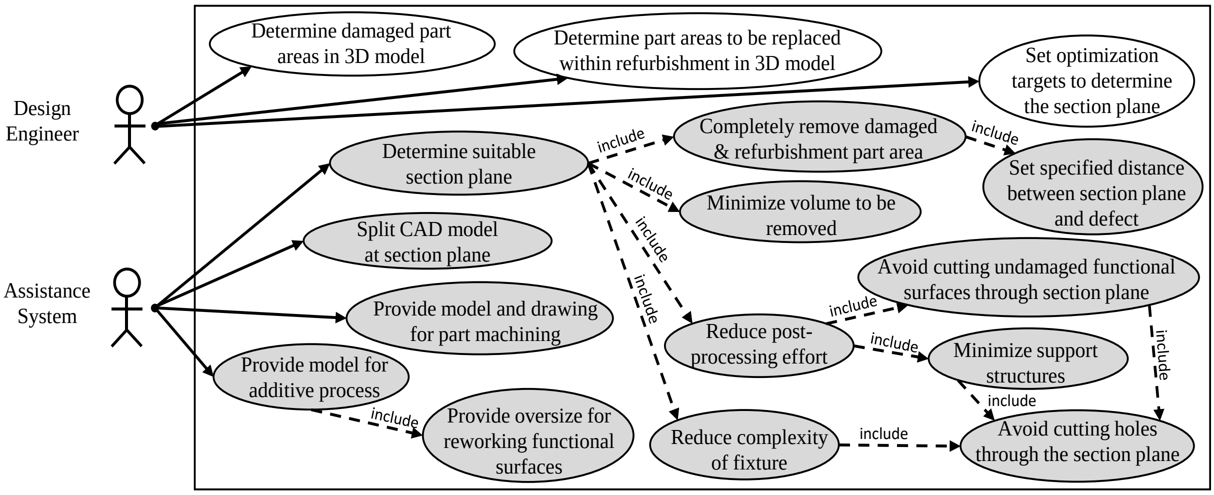


Figure 2. Excerpt from the use case diagram

The system input is the CAD model of the undamaged part. The user defines the damage in the model by extruding a box. The clearance between the damage and the section plane can be controlled by the size of the solid, since the rule is stored in the assistance system that the entire box must be removed. By naming the error extrusion uniquely as “Error”, it can be identified by the program in the structure tree. In order to identify a suitable section plane based on the modified CAD model, the program generates a large number of potentially suitable planes.

To create the planes, a corner of the error extrusion is selected as starting point. The corner with the smallest distance to the parts center of gravity is always selected as starting point. This ensures that all damaged material is removed and the defect is in the cut off volume. The first three planes are generated according to the body surfaces at the starting point (see Figure 3). In the following, further planes are created which are rotated in fixed angular steps $\Delta\alpha$ between 0-90° around the respective body edge at the starting point. The angle increment $\Delta\alpha$ is adjustable by the user in the user interface and controls the accuracy of the results as well as the calculation time of the system. Each generated plane is subsequently evaluated with respect to the evaluation criteria in order to identify the most suitable plane.

On the one hand, the planes are evaluated with respect to the cut off volume. This parameter can be determined by separating the component volume at the respective plane into two separate bodies. The volume is then saved as a parameter. Furthermore, the planes are analyzed with regard to the requirement that no undamaged functional surfaces are cut or cut off. Functional surfaces that are contained as features in the structure tree, e.g. holes, can be identified automatically by their name. Functional surfaces that are not available as features in the CAD model can be identified using surface specifications and tolerances stored in the CAD model. Another possibility is to identify functional surfaces by user input. Likewise, component areas are identified that must be removed by the section plane due to additive refurbishment. The third evaluation criterion is the required support structures. It is analyzed by comparing the angle of a surface normal with the maximum downskin angle, as done in existing systems e.g. by Mbow et al. (2021). In order to generate surface normals for curved surfaces, they are divided into a number of planar surfaces. For this purpose, the volume cut off by a plane can be exported as an STL file, since surfaces are tessellated in the STL format. The system records how many surfaces require support structures, weighted according to their surface area. The maximum downskin angle, which is used as a limit value for this purpose, can be adjusted by users in the input mask. This is necessary because the maximum downskin angle is not a generic value, but depends on the material used, the system and the process parameters.

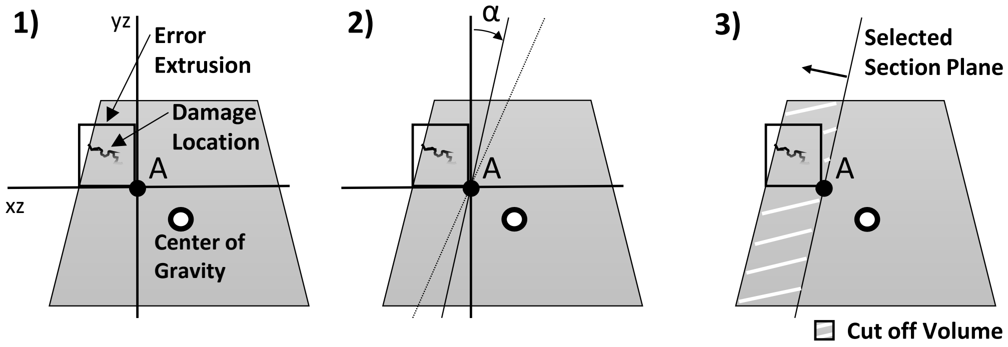


Figure 3. Procedure for generating potential section planes (schematic)

The planes are compared with each other in the program on the basis of the described assessment parameters. The user can assign a weighting to the evaluation criteria in the input mask. Accordingly, an appropriate section plane is determined by the program. The output is on the one hand the model and the technical drawing of the cut component for the part preparation. On the other hand, the file for the LPBF process is created. To do this, the user is first asked which surfaces require rework after the LPBF process. The selected surfaces are accordingly thickened by a parameter stored in the system. Subsequently, in the case of an additive refurbishment, the design engineer may modify the model. Finally, the model is exported as a STL file, which can be used directly for the slicer in the additive repair process. The process flow described is summarized in the following Figure 4.

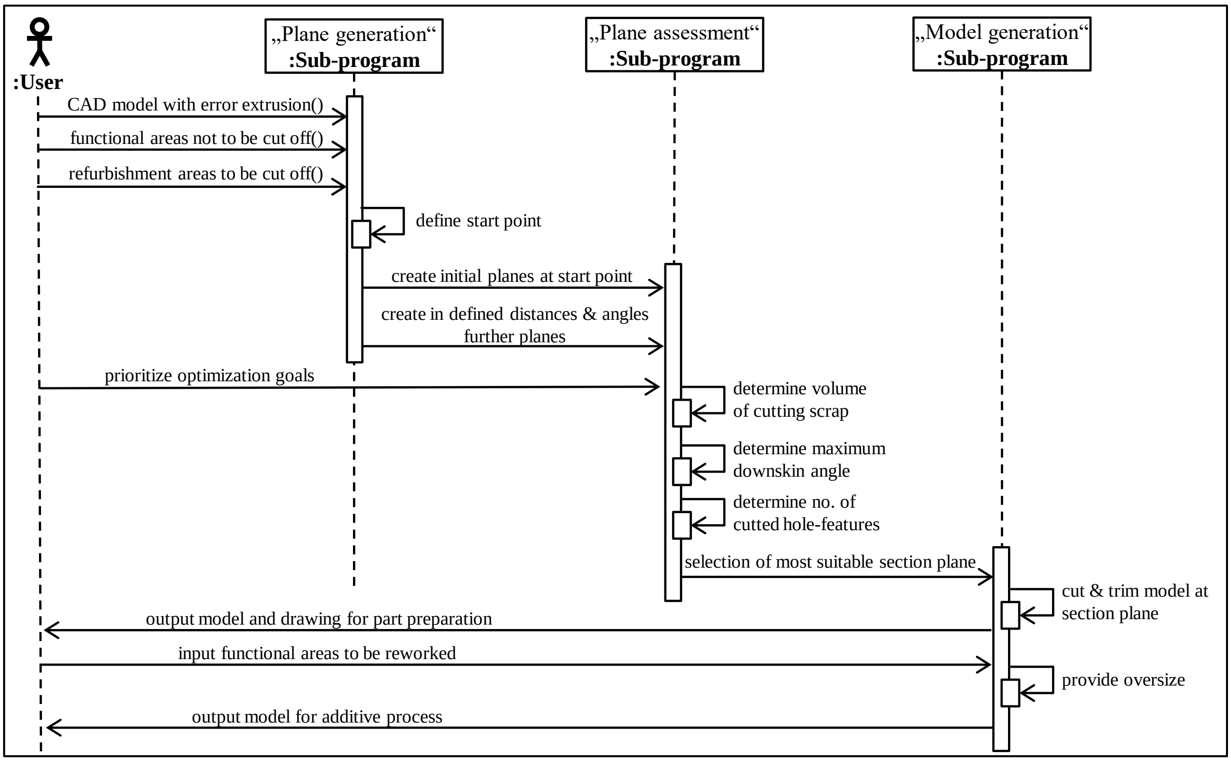
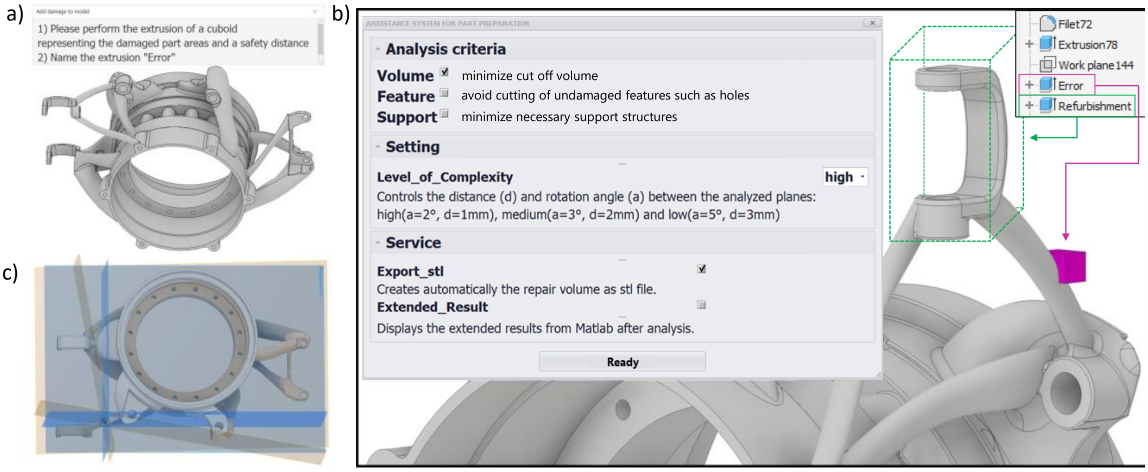


Figure 4. Sequence diagram of the assistance system

4. Application Example

The developed concept is set up as an assistance system in the CAD program Autodesk Inventor Professional 2020 using the Visual Basic for Applications (VBA) programming environment and a Matlab interface. In the following, the application of the assistance system for an additively manufactured wheel carrier of a racing car is presented. The component failed due to cracks in one arm in the early use phase.

Input for the assistance system is the CAD model of the undamaged wheel carrier. The damaged area, which was identified by visual inspection, is extruded in the CAD model as a cuboid with the designation “Error” (see Figure 5). The user can specify in an input mask whether holes may be cut through the section plane. In addition, the user can select surfaces that may also not be cut. In the case of the wheel carrier, this is not necessary because there are no functional surfaces other than the holes in the area of the damage. In addition, component areas can be determined which must be cut off because they are modified as part of the additive refurbishment. In the case of the wheel carrier, particle-filled cavities shall be introduced in the area near the tie rod connection to increase the fatigue strength of the wheel carrier, as described by Ganter et al. (2021b). For this purpose, a cuboid is extruded in this part area and named “Refurbishment”. Furthermore, the user selects which evaluation criterion is prioritized: volume cut off or surfaces requiring support structures. Finally, the user selects whether the complexity of the component is high, medium or low. For the wheel carrier, a high complexity is selected.



1) Please perform the extrusion of a cuboid representing the damaged part areas and a safety distance
2) Name the extrusion "Error"

Analysis criteria
Volume ☑ minimize cut off volume
Feature ☐ avoid cutting of undamaged features such as holes
Support ☐ minimize necessary support structures

Setting
Level_of_Complexity high
Controls the distance (d) and rotation angle (a) between the analyzed planes: high(a=2°, d=1mm), medium(a=3°, d=2mm) and low(a=5°, d=3mm)

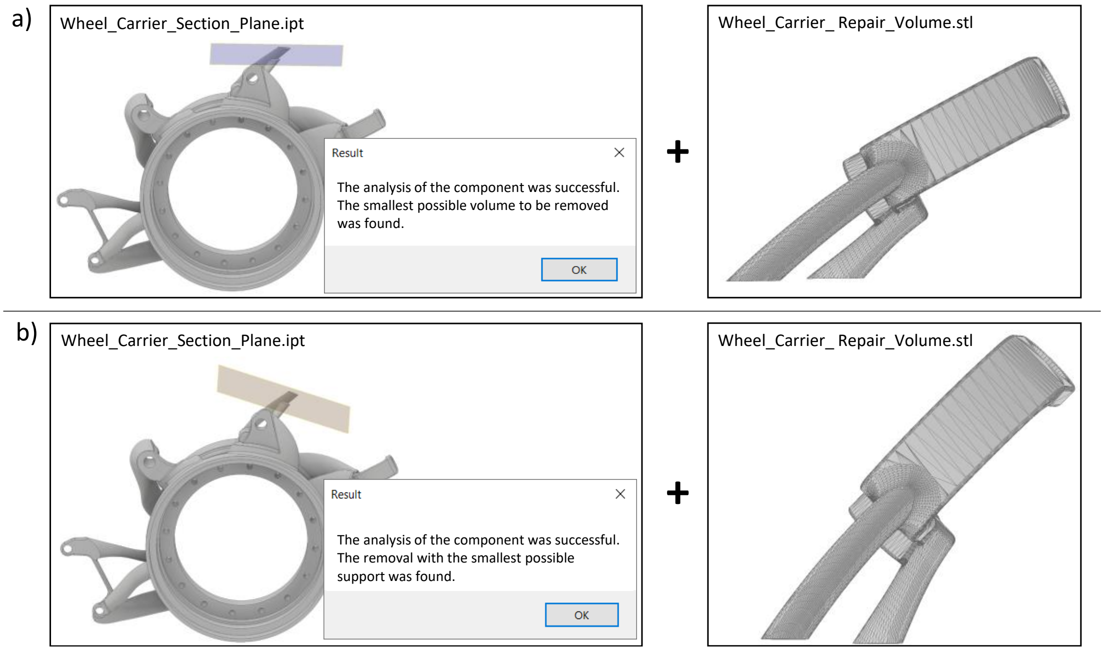
Service
Export_stl ☑
Creates automatically the repair volume as stl file.
Extended_Result ☐
Displays the extended results from Matlab after analysis.

Figure 5. Assistance system for part preparation in a LPBF repair process: a) CAD model of the wheel carrier and request for input of the damage, b) user inputs for the analysis of the wheel carrier, c) visualization of some generated potential section planes

Based on these inputs, the processing in the assistance system takes place. First, the three initial planes are created at the corner of the error volume which has the smallest distance to the part's center of gravity. These are colored blue in Figure 5c. Then, additional planes are created in a fixed angular interval Δα around the edge of the error extrusion. Three of these planes are illustrated in orange in Figure 5c. The angular interval Δα is selected in the system according to the component complexity entered by the user. Thus, the input of the component complexity controls the number of generated planes and thereby significantly influences the calculation time of the tool as well as the possibility to find an optimal plane (comparable to the sampling interval in signal processing). For parts of a high complexity, as in the case of the wheel carrier, the value $\Delta\alpha = 2°$ is stored in the system. The generated planes are analyzed in the system with regard to the evaluation criteria. After the analysis is completed, unsuitable layers are deleted from the model; the most suitable plane remains. The analysis results are documented in a Matlab file and displayed graphically.

For the wheel carrier, the analysis was performed twice. In the first run, it was prioritized that a small volume is removed by the section plane. In the second run, priority was given to the least amount of support structures required. The section planes recommended by the system according to these inputs are shown in Figure 6.

According to the recommended section plane, the model and the technical drawing for milling are created by the system. To generate the file for the LPBF process, the user is first asked which surfaces require rework after the additive material application. For the wheel carrier, two holes are selected, which are thickened automatically by 0.1 mm, which is a parameter stored in the system. Since the wheel carrier is refurbished, the model is then edited by the designer before it is exported as an STL.



The analysis of the component was successful. The smallest possible volume to be removed was found.

The analysis of the component was successful. The removal with the smallest possible support was found.

Figure 6. Results of the system analyses: wheel carrier with the section plane a) removing the least volume, b) requiring the least support structures.

5. Discussion

The application example demonstrates that the developed expert system is suitable for supporting the selection of a section plane. The developed requirements for the assistance system were implemented with the described software concept. For the development of the system, the methodological approach MOKA was followed, which was found to be suitable. In particular, we consider the elaboration of the formal model to be a beneficial element of the approach, since it offers a clear intermediate representation of the knowledge before the implementation of the program in the CAD system.

In order to test the reliability of the developed expert system, it was applied to different components. The system generates successfully a section plane for all considered use cases, which ensures that the damaged part area is completely removed. The calculation time varied for the considered components with the complexity of the component geometry and the size of the component surface. However, the application of the system also demonstrated limitations. The system does not recommend the most suitable section plane with respect to the evaluation criteria under certain circumstances. This is the case for components where the center of gravity resp. the damage is in an adverse position, so that not the most suitable corner of the error extrusion is selected as starting point for generating the planes. Thereby the system may recommend a section plane that removes more material than necessary.

Another reason for an inaccurate recommended section plane is that a limited number of planes are generated by the system and analyzed as possible section planes. The planes are generated at an angle between 0–90° to one edge of the error extrusion. Accordingly, no planes are analyzed as possible section planes at an angle $\alpha > 0$ to two edges of the error extrusion.

Furthermore, the system has limitations in the detection of functional surfaces like holes. The CAD-based expert system can identify holes or other functional areas through feature recognition. This offers the advantage of high reliability, provided there is a consistent design style in the CAD models, meaning that holes, for example, were created using the CAD system's hole tool. Otherwise, the system does not detect when potential section planes intersect holes, so the recommendation of the assistance system is inaccurate.

Another potential source of error for the system-based section plane recommendation is the manual extrusion by the design engineer, which can be error-prone by not representing the real damage of the part. To avoid this potential weakness in the additive repair process chain the input of the part damage could be automated. For this purpose, a 3D scan of the damaged component can be created and automatically compared with the model of the undamaged component. However, this approach is only feasible for damages detectable by a 3D scan. This does not apply to cracks, for example.

A prerequisite for the use of the expert system is that the CAD model of the component is available. If this is not the case, e.g. for very old components, a model can be created by a 3D scan or manually reconstructed. For the assistance system it is not necessary that the undamaged part areas are completely modelled. However, the center of gravity of the model should be close to reality.

In addition, the system requires the part model to be in the file format of the CAD system in which it is implemented. This drawback could be overcome by using geometry detection instead of feature recognition. This would offer the additional advantage that functional surfaces such as holes which are not created as feature are identified by the system. Furthermore, STL data could be used as system input which is expected to greatly reduce computation time by eliminating the need to convert the model to STL for assessing the necessary support structures. However, the estimated effort for implementing geometry detection is much higher than for feature recognition.

6. Conclusion and Outlook

In this contribution, a software concept is presented that provides automated support for the selection of a suitable section plane for additive repair processes using LPBF. The CAD-based system generates a large number of potential section planes and evaluates them with respect to the volume cut off and the support structures required in the subsequent LPBF process. In addition, the evaluation takes into account whether holes or functional areas will be cut (off).

In the future, different optimization algorithms will be examined with respect to their suitability for identifying the most suitable section plane. In addition, further evaluation criteria for the selection of the section plane could be stored in the system, e.g. the consideration of the surface roughness and the stair step effect. For the goal of automating the additive repair process chain, future work can be dedicated to further process steps, e.g. the generation of the part model by a 3D scan. The presented assistance system could also be extended to configure a suitable fixture for mounting the part in the installation space of the LPBF system based on the recommended section plane and the part geometry.

Acknowledgments

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