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Scalable Additive Repair with Powder Bed Fusion using a Laser Beam

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Abstract

Additive repair with powder bed fusion using a laser beam for metals (PBF-LB/M) offers a significant potential for the sustainable restoration of small metallic parts. Larger, high-value parts remain challenging for repair with PBF-LB/M, as the limited build volume of these machines constrains its applicability. This paper presents a new scalable additive manufacturing system called MESSIAH, that is designed to repair parts with up to 2500 mm in height. A repair process chain, addressing key challenges such as damage analysis, repair geometry design, and the preparation of the machine and part environment, is developed. The latter is particularly critical for ensuring precise alignment, sealing, and thermal control during processing. MESSIAH enables scalable additive repair for large components, reducing material usage, increasing process reliability, and extending the service life of large metallic components.

Keywords: additive repair; powder bed fusion by using a laser beam (PBF-LB/M); scalable

1. Introduction

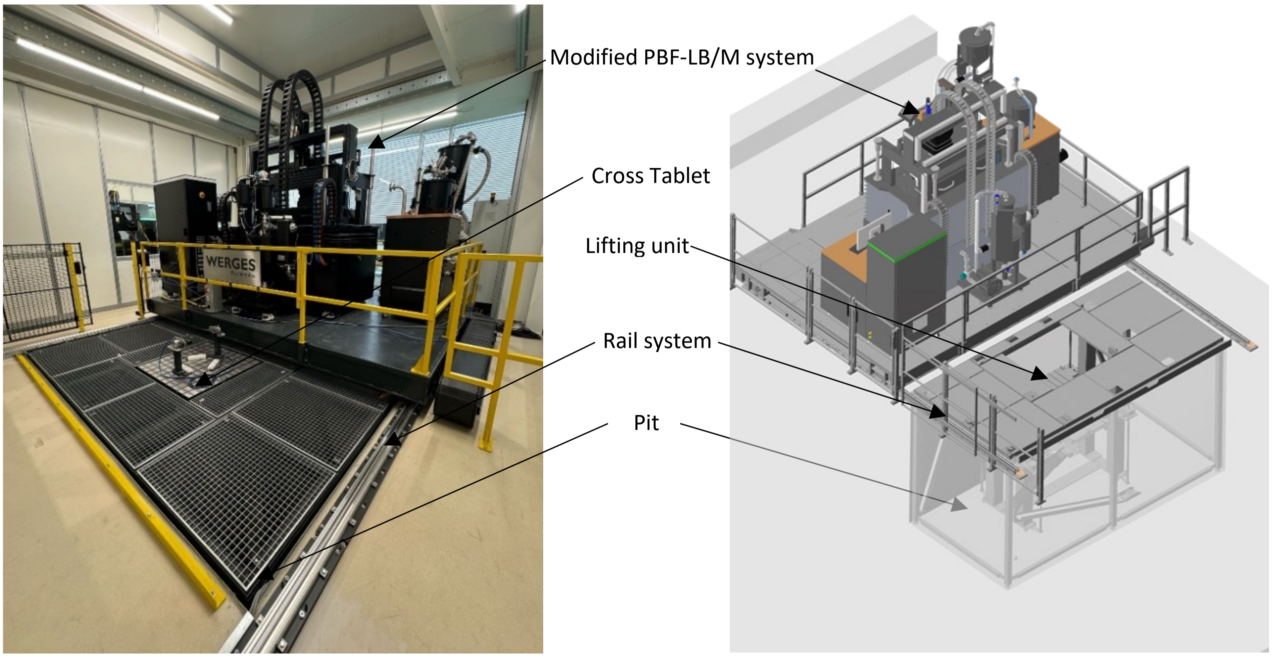
Additive manufacturing (AM) has become a key technology for the manufacturing and repair of metal parts, offering significant benefits in terms of material efficiency, geometric flexibility, shorter lead times and improved sustainability across the entire product life cycle (Rahito et al., 2019). Additive repair where damaged or worn parts are selectively rebuilt to restore their function, often at a fraction of the cost and time compared to full replacement, is one of the most challenging applications (Kanishka & Acherjee, 2023). In industries such as aerospace (Vafadar et al., 2021, Liu et al., 2017), power generation, and heavy engineering (Andersson et al., 2016) where parts are highly complex, expensive, and exposed to harsh operating conditions, the ability to perform precise and reliable additive repair is particularly critical. Several AM processes have been developed and applied for repair purposes. One of the most established is Directed Energy Deposition (DED) in which metal feedstock (usually powder or wire) is fed into a melt pool created by a focused energy source such as a laser or electron beam (Aprilia et al., 2022). The DED process offers the advantage of high deposition rates typically at about 8.3 g/min (Ahn, 2021, Wang et al., 2023) and large build volumes for repair, making them suitable for large-area restoration tasks (Heralić et al., 2012, Williams et al., 2016). However, DED often lacks in the build resolution and surface quality required for parts with intricate geometries or tight dimensional tolerances, primarily due to its larger melt pool size, larger deposit resolution, and limited layer control (Sames et al., 2016).

While DED is well-suited for large-scale and general repairs, PBF-LB/M is superior in high-precision and smoother surface applications (Lachmayer et al., 2025, Ehlers et al*.,* 2020). In the PBF-LB/M, thin layers of metal powder are coated in a powder bed and selectively fused using a laser under a controlled inert atmosphere (Chowdhury et al., 2022). PBF-LB/M achieves high geometric fidelity and is particularly effective in cases requiring tight tolerances and complex internal features, which are increasingly common in modern engineered systems *(*Herzog et al., 2016, DebRoy et al., 2018*)*. Its application in additive repair is growing, especially for high-value parts, e.g. turbine blades (Aust & Pons, 2019), injection molds (Asnafi et al., 2020), and biomedical implants (Zhang et al., 2023). For this, precision and material integrity are required. Nevertheless, PBF-LB/M is primarily limited to small- and medium-sized parts until now *(*Andersson et al*.,* 2016, Merz et al*.,* 2023*)*. This is mainly due to restrictions in build volume and the need for precise environmental control. This limitation presents a significant barrier for its wider use in the repair of large-scale industrial parts (Thompson et al., 2016). Up to date, the expanding of PBF-LB/M for larger components offers great potential for improving sustainability by extending the life of critical high-value parts, minimizing material waste, and reducing carbon footprints across product lifecycles (Taghian et al., 2023, Nycz et al., 2016*)*.

Previous studies highlight the potential of PBF-LB/M for repair applications by characterizing the microstructural development and corresponding mechanical properties in materials such as nickel-based alloys, e.g. Hastelloy X, stainless steel as 17-4PH (1.4542), and aluminum alloys such as AlSi10Mg (Zghair & Lachmayer, 2017). Additionally, Andersson et al. advanced this technology by developing and qualifying PBF-LB-based additive repair for Siemens' SGT-800 and SGT-700 DLE burners, which have part heights of approximately 720 mm. These efforts validate the feasibility of using PBF-LB for repairing relatively small to medium-sized parts and demonstrate successful integration in industrial contexts, addressing challenges related to repair design, material behavior, and test setup. However, despite these advancements, the application of PBF-LB for large-scale component repair remains a research target and introduces a new set of interrelated challenges. These include maintaining geometric precision (Merz et al., 2023*)*, managing thermal distortions (Müller et al., 2023), ensuring machine-part interaction stability (Nycz et al., 2016*)*, achieving effective environmental sealing (Andersson et al., 2016), and handling complex repair-specific data process chain (Ganter et al., 2022). Conventional PBF-LB/M systems are not inherently designed for component repair, especially at large scales, and typically lack integrated process chains tailored to the unique requirements of hybrid repair applications. To overcome these limitations, the MESSIAH (Machine for Scale-Independent Selective Laser Melting) system has been developed as a large-format PBF-LB/M platform capable of repairing parts up to 2500 mm in the height.

2. The Scalable System Overview

The novel large-scale additive manufacturing system enables the manufacturing of metallic parts beyond the build volume constraints of conventional PBF-LB/M machines. The concept allows for parts up to 2500 mm in height (Niedermeyer et al., 2025). In addition to producing new parts, the system enables the repair of existing damaged parts by building directly onto them within a scalable and modular process environment. Within the process chamber, the build-up volume is limited to 250 mm in diameter, while the underlying component can reach a cross-section of 1000 × 1000 mm². These dimensions are scalable through further modular extensions of the system. A schematic overview of the system is provided in Figure 1.



(a) (b)

Fig. 1. Technical Setup of the Large-Scale Additive Manufacturing System; (a) Isometric View from the Process Chamber Side; (b) Isometric View from the Front of the PBF-LB/M

The architecture comprises three core subsystems:

- A linear rail-guided motion platform,
- An elevating unit with cross-table positioning,
- A PBF-LB/M module for localized layer-by-layer processing

The rail system enables longitudinal movement of the entire PBF-LB/M unit, ensuring precise alignment above the workpiece along the repair path. A lifting unit, integrated into a pit, vertically positions and elevates the component via a cross-table with two translational degrees of freedom perpendicular to the build height. A custom-designed clamping system further allows for angular adjustment and three-dimensional positioning relative to the process plane, enabling highly adaptable alignment to complex geometries. The PBF-LB/M module itself consists of a build chamber with an open-bottom configuration (Ø 250 mm, height 250 mm), specifically designed to allow vertical insertion of scalable parts into the process zone. A fully integrated powder handling system supports both recoating and powder recovery functions, while the laser exposure unit features precision scan optics for targeted energy input. To ensure operator safety and environmental protection, the entire module is enclosed in a laser-safe housing that also guarantees secure powder containment. The process atmosphere is stabilized by a sealed inert gas system, operating with argon to prevent oxidation and ensure consistent processing conditions. Key machine specifications are two fiber lasers with 1070 nm wavelength and maximum laser power of 400 W, which provide sufficient energy density for the repair of demanding materials. The choice of material depends on the part to be repaired. While the build chamber itself limits the deposition area in the recoating plane to a diameter of 250 mm, the machine concept allows for the repair of components up to 2500 mm in total length. Additionally, the already existing portion of the part outside the build area can reach dimensions of up to 1000 × 1000 mm², making the system suitable for large-scale industrial repair scenarios.

3. Process Chain for Scalable PBF-LB/M Additive Repair

In order to enable the efficient and repeatable repair of scalable parts using PBF-LB/M, a structured and scalable process chain is essential. This process chain describes the additive repair workflow from initial assessment to final processing, while remaining compatible with ongoing digitalization and future automation strategies. The process chain presented here is inspired by the additive remanufacturing workflow described by Sato et al. (2022), which focused on small-scale applications. However, their model does not address the specific technical challenges of scaling the process to parts up to 2500 mm, which will be examined in detail in the next section. To bridge this gap, the process chain is systematically adapted to the requirements of large-scale additive repair. Based on a comprehensive literature review, several additional process steps are systematically formalized and redefined. These include conducting a detailed damage analysis, adapting the system to the specific repair requirements, defining a tailored repair strategy, and preparing the system for execution.

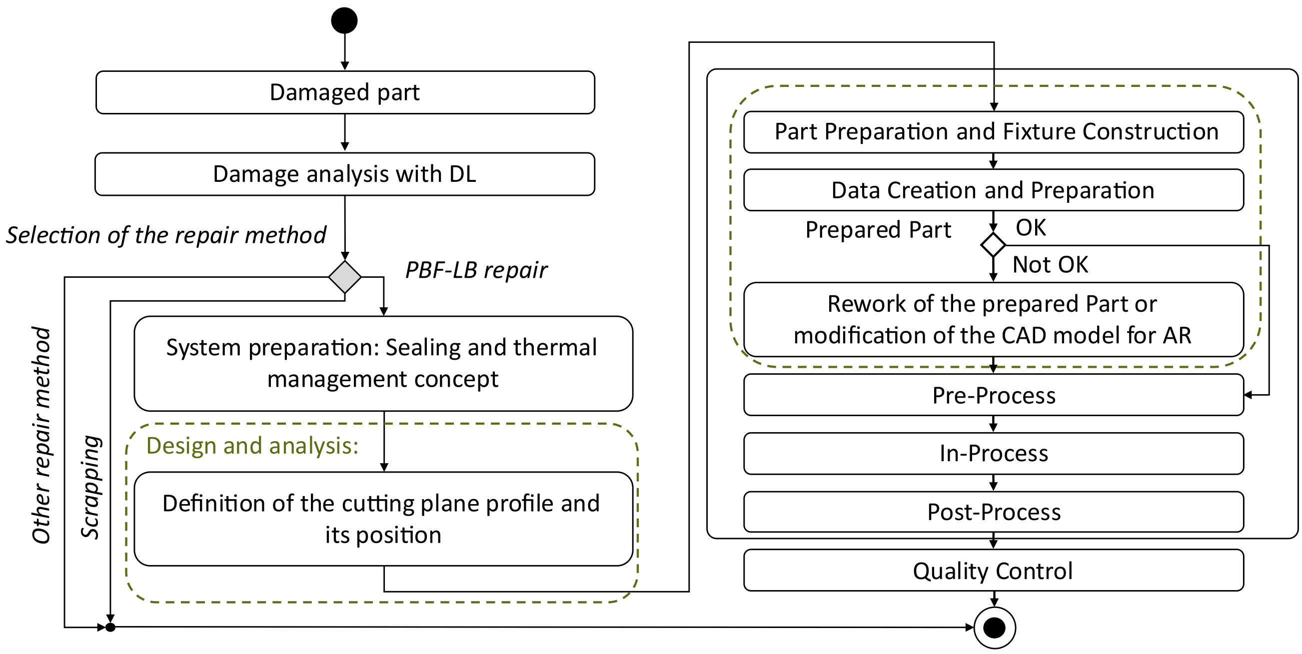


Fig. 2. Process Chain of the Scalable Additive Manufacturing System

The adapted process chain addresses key scalability challenges like fixation design, sealing, thermal management, and distortion control. These are integrated into the workflow phases. Figure 2 illustrates the adapted process chain developed for the MESSIAH system, showing how these challenges are addressed throughout the process. These challenges, represented by the green circles, define additional essential steps required for scalability and are integrated directly into the workflow phases to ensure a robust repair process.

4. Challenges in Scalable PBF-LB/M Additive Repair

The following section examines each of these challenges in detail, outlining their relevance to large-scale additive repair and, where applicable, proposing approaches for their resolution. The upscaling of additive repair processes to large-format parts introduces a series of critical, scale-dependent challenges that extend beyond conventional repair process chains (Sato et al., 2022). Within the context of scalable PBF-LB/M repair, four core technical aspects have been identified as prerequisites for process stability and scalability:

- Fixation System
- Sealing System
- Thermal Management and Distortion Control
- Design and Analysis

4.1. Fixation System

The precise positioning and secure fixation of large-scale components during the additive repair process shows an important factor, for which a dedicated clamping and support system is being developed, as illustrated in Figure 3. The setup features a pneumatic clamping unit mounted above the workpiece fixture, which allows a repeatable and force-controlled fixation. The workpiece itself is held by a customized clamping element, which is specifically adapted to the geometry of the part. This clamping element is connected to a cross table that enables precise positioning in the horizontal plane, while vertical adjustment is realized through a lifting system. The integration of pneumatic clamping not only facilitates automated handling but also reduces setup times and increases process reliability. This configuration serves as the basis for scalable fixturing concepts tailored to large-format components in the additive repair workflow.

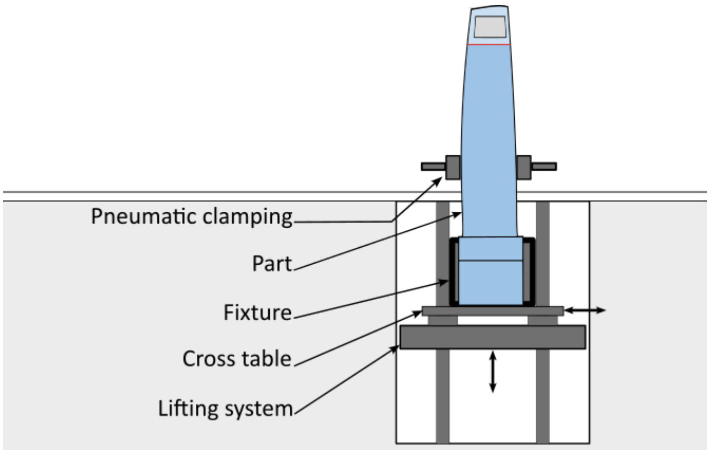


Fig. 3. Schematic view of the fixation system on a turbine blade in the pit

4.2. Sealing System

Maintaining a controlled, contamination-free environment in additive repair relies on dedicated sealing systems (Figure 4). Positioned between the processing chamber and the workpiece, these systems isolate the application area from external influences. This isolation is crucial to prevent uncontrolled powder dispersion and to maintain consistent process conditions near the laser interaction zone. The envisioned design consists of a form-adapted sealing unit that would enclose the applied part area from above. The sealing interface is planned to be integrated directly into the tool head assembly, forming close contact with the workpiece. The setup would enable effective powder retention and protection against external contamination.

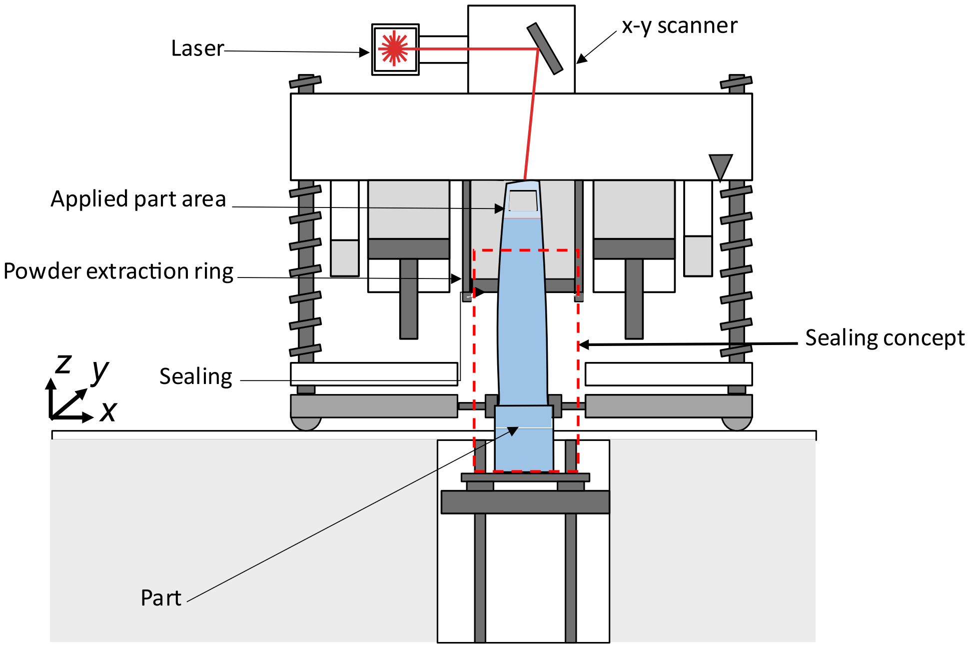


Fig. 4. Sealing System

4.3. Thermal Management System

Thermal management represents another key challenge in the scalable implementation of additive repair processes (Sato et al., 2022). A major objective is to develop a thermal management concept (Figure 5) that effectively minimizes temperature gradients within the part, thereby reducing the formation of residual stresses. This contributes significantly to enhancing process stability and improving the quality of the repaired parts. As an initial approach, heating sleeves are investigated.

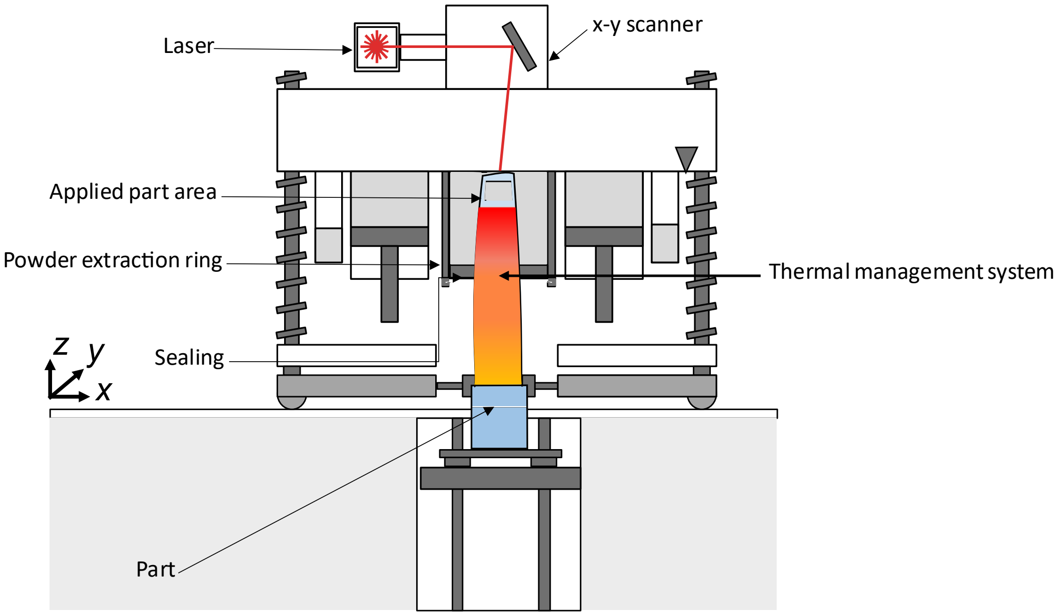


Fig. 5. Thermal Management System

These can be implemented either as stationary units integrated into the manufacturing system or as component-mounted devices directly attached to the workpiece. They enable conductive heating and allow for precise temperature control throughout the repair process. In addition to this, alternative methods such as inductive heating systems are being explored. These systems offer contactless energy input and are well-suited for integration into automated process chains. The selection of the most suitable technology depends on several factors, including the geometry of the component, material behavior, and the system's overall integration requirements.

4.4. Design and Analysis

The digital workflow for scalable additive repair using PBF-LB/M begins with a damage analysis, which is crucial for identifying, localizing, and characterizing defects in complex parts. This step utilizes deep learning-based (DL) algorithms capable of interpreting geometric and surface features directly from 3D scan data or CAD models. The algorithms classify defect types such as cracks, surface erosion, or material loss, and determine their precise location and extent. The resulting defect data is transferred to an automated decision-support system, which evaluates whether the identified damage is suitable for PBF-LB/M repair or if an alternative additive process is more appropriate. This decision is based on criteria including defect geometry, location, wall thickness, and the required mechanical performance of the repaired region. For example, volumetric or deeply embedded defects may be assigned to DED, while smaller surface-level flaws may be routed to PBF-LB/M. As an immediate outcome of this DL-based damage analysis, the design and analysis of the part to be repaired is initiated. Once the damage is confirmed as suitable for PBF-LB/M, the workflow transitions to the part preparation phase. In the part preparation phase, the affected part is oriented so that the repair surface aligns with the positive z-direction, establishing a standardized spatial reference for subsequent data processing and repair planning. Following this alignment, the part is digitally segmented into functional zones. A sectioning operation divides the part into two bodies: a repair zone, where additive material will be applied, and a reference zone, which remains unchanged to preserve critical structural integrity. This segmentation ensures that the additive process targets only the necessary regions, maintaining both geometric accuracy and compliance with structural requirements. The next step in this workflow is plane placement, which enables the slicing of the error cube into individual cross-sections for further evaluation and potential optimization. Plane placement represents a key step in preparing for the analysis of section planes. In the initial step, the tertiary input represented by the error cube is used as the starting point for placing the angular boundary planes. These boundary planes are directly dependent on secondary input parameters and serve to define the maximum inclination angles of the part for a potential repair plane. First, the z-axis distance is used to determine the lower edges of the cube. Based on these edges, the boundary planes are created. Subsequently, a secondary input parameter is used to generate a user-defined number of planes between the boundary and base planes of the cube. This method enables precise and controlled placement of the section planes for the subsequent analysis. In this context, the cube in the Figure 6 represents the part preparation for the cutting plane. The goal of component preparation is to establish a fundamental data and information basis for the process of plane optimization and for evaluating the generated section planes, while also preparing the part for user-guided defect isolation.

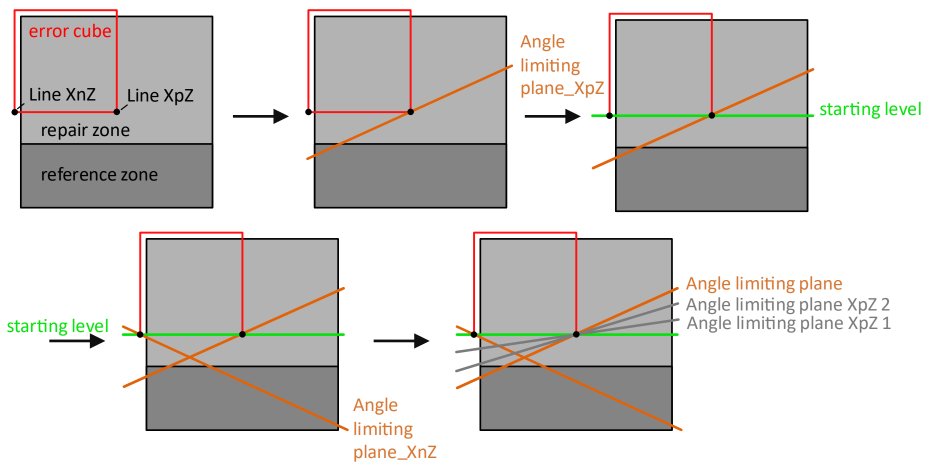


Fig. 6. Part preparation process for additive repair

5. Conclusion

This work identifies key challenges for scalable additive repair of metal parts, maps them onto the MESSIAH system, a hybrid manufacturing system for parts up to 2500 mm in height, and defines them within a structured process chain. While no complete solutions are yet provided, the part preparation phase, featuring digital damage detection and automated cross-sectional slicing, has already been implemented, demonstrating measurable time and cost savings. The remaining areas, including sealing, fixturing, and thermal management, are currently under investigation. Together, these activities establish the framework for a modular, application-oriented process chain, supporting the future industrial readiness of scalable additive repair workflows.

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